Series II, Volume 2 March 21, 1957 Number 3

# BULLETIN

OF THE

## AMERICAN PHYSICAL SOCIETY

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INCLUDING THE

PROGRAMME OF THE

## 1957 MARCH MEETING

AT

PHILADELPHIA, PENNSYLVANIA

March 21–22–23, 1957

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# BULLETIN

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# Table of Contents

Programme of the 1957 March meeting at Philadelphia . . . . . 114

Author index to papers presented at the 1957 Philadelphia meeting . . . . . 159

Second announcement of the 1957 Spring meeting at Washington . . . . . 161

Calendar of meetings and deadlines . . . . . 161

Instructions for preparation of abstracts . . . . . 161

Minutes of the 1956 Monterey Meeting . . . . . 162

Officers of Divisions . . . . . 163

Form for making advance reservations for events at Philadelphia meeting . . . . . 164

March 21, 1957 Series II, Vol. 2, No. 3

# BULLETIN

OF THE

# AMERICAN PHYSICAL SOCIETY

1957 March Meeting at Philadelphia, March 21–23, 1957

THE American Physical Society will hold its **1957 March meeting** (we have found no other designation for this one, despite the fact that two meetings of 1957 are scheduled for March) at **Philadelphia,** in the buildings of the **University of Pennsylvania, on Thursday, Friday, and Saturday, March 21, 22, and 23.** So accustomed are we to holding our March meetings in hotels, this locale will give us a surprising and a pleasant contrast. Normal for March is the predominance of our Divisions of High-Polymer Physics and Solid-State Physics, to which for the second time the younger Division of Chemical Physics adds itself as a patron. The other parts of physics, so overpowering at most of our conventions, contribute only a few papers to this one, though not quite so few as last year. Philadelphia is one of the greater cities where we meet too seldom (the latest occasion was in 1940) because of the proximity of New York and Washington where we do have the habit of regularly convening. The Local Committee is headed by C. W. Ufford and S. D. Morgan of the University of Pennsylvania, to whom and to whose colleagues we owe much.

The **Benjamin Franklin Hotel**, at Ninth and Chestnut Streets, has set aside rooms for our members, who incidentally have been notified of this fact in two prior issues of the *Bulletin:* any who have not yet made reservations should do so at once, mentioning in their letters that they are coming for our meetings. To go from hotel to University, walk south along Ninth Street to Walnut Street and take a street-car on the latter: since not all of the Walnut-Street cars go to the University, ask the conductor before boarding whether his is one that does: it is about a ten-minute ride to 33rd and Walnut where you get off. Coming back, the car will follow Chestnut Street and stop at the corner where the hotel is.

The **registration desk** will be located in the Physical Sciences Building of the University of Pennsylvania. Here will be the distribution of registration cards—the registration fee will be one dollar—and the sale of tickets to the banquet of Friday evening and the social of Thursday evening (see below). There will be blackboards adjacent to the registration desk for notices of messages and for the names of the post-deadline papers if any: consult them frequently.

Our **Division of High-Polymer Physics** has organized five sessions, partly of invited and partly of contributed papers, occupying each of the half-days of the meeting excepting Saturday afternoon. By "organized" is here meant not only that they chose the invited papers but also that they arranged the contributed papers, doing thus a service to the Secretary and the Society for which the former is grateful and the latter will be.

Our **Division of Solid-State Physics** organized five symposia—including one on the quite unsolid topic of liquid helium—and in fact might be credited, or debited, with five and a half, in view of the statement which follows. Also it sprinkled a few other invited papers among the other sessions.

Our **Division of Chemical Physics** organized two symposia, but of one of these it shares the sponsorship with the Division of Solid-State Physics, leaving, let us say, one and a half to its account.

**Session L on Friday morning** consists of all of the invited papers lying outside of the provinces of the three Divisions: one in fundamental theory and three in nuclear physics. The Secretary is very happy that the four speakers—W. F. G. Swann, F. R. Metzger, Walter Selove, and Abraham Klein—were willing to give these papers despite the prospect of a slim audience, of which they were duly warned: may the warning prove excessive!

**Two hundred and thirteen contributed papers** (a number to be compared with 201 in 1955 and 224 in 1956) have been arranged in twenty sessions. Nine have been assigned to the session "nuclear and

theoretical physics" and ten to the session "general physics," these last including some identifiable as chemical physics. Of the disposition of the thirty-one in high-polymer physics, I have already spoken. The remaining one hundred and sixty-three belong more or less in solid-state physics, and what with their multitude and with the plethora of invited papers in the same field, the task of arranging the solid-state papers reasonably well was difficult, and the ideal of arranging them without undesirable coincidences in time was utterly unattainable. This problem always arises. On the present occasion it was solved largely by the efforts of E. Burstein, the Secretary of the Division of Solid-State Physics.

The **Business Meeting of the Division of High-Polymer Physics** will be part of Session E on Thursday afternoon, and the **Business Meeting of the Division of Chemical Physics** will be part of Session U on Saturday morning. The Business Meeting of the Division of Solid-State Physics will be held at an unlikely time and place, 6 P.M. of Thursday in the Indian Arts Gallery of the University Museum, if the members of the Division can distract their attention from the party then and there going on.

The **Council of the American Physical Society** will meet on Thursday afternoon at two, in a place of which the members will be notified by special message.

The **banquet of the Society** will be held on **Friday evening** in the Crystal Ballroom of the Benjamin Franklin Hotel: President Gaylord P. Harnwell of the University of Pennsylvania will begin the after-dinner programme; T. G. Fox of our Division of High-Polymer Physics will speak and so will Gerhard Herzberg of our Division of Chemical Physics; and Cyril S. Smith will give an address under the title "Physical Metallurgy and the Physics of Metals." The price will be five dollars. Bookings may and should be made in advance by use of the appropriate form on page 165 of this Bulletin.

There will be a **social hour** (so designated by the Local Committee in spite of the fact that it spreads over two hours) in the impressive setting of the Indian Arts Gallery of the University Museum on **Thursday afternoon from 5 to 7.** Beer, soft drinks, pretzels, and potato chips are promised. The price will be $1.25 to men and zero to women, and bookings may be made in advance by use of the appropriate form on page 165 of this Bulletin. Here we do most urgently advise the use of the form, for the capacity of the room is distinctly under the prospective attendance at the meeting. Those who reserve in advance will find their tickets waiting at the registration desk: others must take their chance.

The third of the forms on page 165 pertains to the **ladies' programme.** Gray Line buses have been chartered to leave the Benjamin Franklin Hotel at two o'clock on Friday for a two-hour tour of historic Philadelphia, this to be followed by tea at 4:30 P.M. in the Franklin Room of the hotel. The cost of all this will be $2.57 per person. Since the ladies will probably not read this Bulletin, their husbands and escorts are charged to make advance reservations for them. Tickets will be sold at the special ladies' desk in the hotel (on the mezzanine), and this desk will be staffed from 9 to 5 on Thursday and Friday to offer "any needed information." Philadelphia is rich in sites and buildings of great historic interest, many of which are within easy walking distance of the hotel, while others such as the very notable art gallery are easy of access by taxi. The people at the desk will tell how to get to such more distant places as Longwood Gardens and Valley Forge.

To get back to business: **post-deadline ten-minute papers,** pertaining to very recent achievements of very special importance, will be considered for admission to a special supplementary programme if the abstracts are received at the office of the Society (the address below) not later than Friday, March 15. The abstracts must be composed according to the usual rules, and two copies must be submitted of each: they will not be published. The titles of such papers as may be accepted will be written on a blackboard near the registration desk, and these papers will be scheduled for presentation at the end of Session R.

**Prospective meetings and deadlines** of the Society are listed on page 162 of this Bulletin, together with instructions for the preparation of abstracts. The second announcement of the 1957 Spring Meeting at Washington, with information about hotels, will be found on page 161.

**Errata** pertaining to abstracts in this issue will be published in a subsequent issue of this Bulletin if received not later than Monday, March 25, by Miss Ruth Bryans, American Institute of Physics, 57 East 55th Street, New York 22, New York. Do not send in the abstracts marked with corrections. Write out the corrections in the form "Instead of . . . read. . . ." The privilege of publishing an erratum is not meant to provide either an opportunity of publishing new data or an opportunity of replacing material cut out because the abstract was too long.

KARL K. DARROW, *Secretary*
American Physical Society
Columbia University
New York 27, New York

# EPITOME OF THE 1957 PHILADELPHIA MEETING

(Personal names are those of invited speakers. DHPP stands for Division of High-Polymer Physics, DSSP for Division of Solid-State Physics, DCP for Division of Chemical Physics.)

## Thursday Morning

| | | |
|---|---|---|
| 10:00 | A. | DCP: dielectric properties of solids: Matthias, Smyth, Cole, Hoffman. Museum. |
| 10:00 | B. | Magnetic materials. Houston. |
| 10:00 | C. | Compound semiconductors; R. W. Smith. Irvine. |
| 10:00 | CA. | Metals and alloys. A-2. |
| 9:30 | D. | DHPP: Litovitz; high-polymer physics I. A-1. |

## Thursday Afternoon

| | | |
|---|---|---|
| 2:00 | E. | DHPP: Hammer; high-polymer physics II.; Business Session. A-1. |
| 2:00 | F. | DSSP: high-magnetic-field effects in metals and semiconductors: Steele, Swanson, Galt, Keyes, Burstein. Irvine. |
| 2:00 | G. | Structure of ferroelectric and magnetic materials; magnetic resonance. Museum. |
| 2:00 | H. | Semiconductor surface phenomena; whiskers. Houston. |
| 2:00 | HA. | General physics. A-2. |
| 6:00 | | Social hours. DSSP Business Meeting. Indian Arts Gallery. |

## Friday Morning

| | | |
|---|---|---|
| 9:30 | J. | DSSP: nuclear magnetic resonance: Redfield, Benedek, Shulman, Reif, Lowe. Museum. |
| 9:30 | K. | Elemental semiconductors. Irvine. |
| 9:30 | L. | Swann, Metzger, Selove, Klein. A-2. |
| 9:30 | LA. | Tinkham; cryogenics. Houston. |
| 9:00 | M. | DHPP: Hughes, Burnett, Flory. A-1. |

## Friday Afternoon

| | | |
|---|---|---|
| 2:00 | N. | Tobolsky: high-polymer physics IV. A-1. |
| 2:00 | P. | DSSP: liquid helium: Atkins, Roberts, Fairbank, Garwin. Museum. |
| 2:00 | Q. | Magnetic effects in semiconductors. Irvine. |
| 2:00 | R. | Nuclear and theoretical physics; post-deadline papers, if any. A-2. |
| 2:00 | RA. | Dislocations and allied topics. Houston. |

## Friday Evening

| | | |
|---|---|---|
| 7:00 | | Banquet of the American Physical Society: Harnwell, Fox, Herzberg, Cyril S. Smith. Crystal Room. |

## Saturday Morning

| | | |
|---|---|---|
| 9:30 | S. | DSSP: double magnetic resonance: Feher, Cotts, Tanttila, Scovil. Irvine. |
| 9:30 | T. | Herman; solid-state theory. A-2. |
| 9:30 | U. | DCP: high-temperature vaporization: Gilles, Chupka, Margrave, Searcy. Houston. |
| 9:00 | V. | DHPP: Pao: high-polymer physics V. A-1. |
| 9:30 | VA. | Irradiation effects (metals and insulators). Museum. |

## Saturday Afternoon

| | | |
|---|---|---|
| 1:30 | W. | DSSP: theoretical topics: Brueckner, Ross, Luttinger, Watson. Museum. |
| 1:30 | X. | Goldberg; transport, diffusion and lifetimes of carriers. Houston. |
| 1:30 | Y. | Alkali halides; luminescence. A-2. |
| 1:30 | Z. | Irradiation effects; semiconductors. A-1. |

# PROGRAMME

THURSDAY MORNING AT 10:00

Museum Auditorium

(J. R. PLATT presiding)

## *Chemical Physics*

## *Symposium of the DCP on Dielectric Properties of Solids*

**A1. Ferroelectricity in 1956.** B. J. MATTHIAS, *Bell Telephone Laboratories.* (30 min.)

**A2. Shape and Rotational Freedom of Polar Molecules in Crystals.** C. P. SMYTH, *Princeton University.* (30 min.)

**A3. Dielectric Properties of Solid Hydrogen Halides.** R. H. COLE, *Brown University.* (30 min.)

**A4. Theory of Dielectric Relaxation in Molecular Crystals.** J. D. HOFFMAN, *National Bureau of Standards.* (30 min.)

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THURSDAY MORNING AT 10:00

Houston Hall Auditorium

(C. ZENER presiding)

## *Magnetic Materials*

**B1. Approximate Simple Expressions for the Demagnetizing Factors of the General Ellipsoid.*** HENRI AMAR.—In the theory of the properties of fine ferromagnetic particles, the shape anisotropy and the magnetostatic energy[1] have been playing an increasing role. Consequently, a greater use is made of the demagnetizing factors of the general ellipsoid. Extremely useful tables and charts for the demagnetizing factors have been published by Stoner[2] (ellipsoids of revolution only) and by Osborn.[3] Osborn gives the expressions for these factors as functions of the axial ratios $b/a$, $c/a$ ($a \geq b \geq c$ semi-axes). Unfortunately, these functions are so unwieldy as to be of rather limited use in theoretical computations such as minimum energy problems. However, a close scrutiny of the tables and charts given by Osborn suggests that approximate and simpler analytical expressions may be found that can replace the rigorous expressions with a relatively small error. A set of these approximate expressions has been derived and is proposed. For cases where higher accuracy is required, means of improving the proposed expressions are indicated that are based on the structure of Osborn data.

* This work was supported by the Magnetics Research Program of The Franklin Institute Laboratories for Research and Development.

[1] E. C. Stoner and E. P. Wohlfarth, Phil. Trans. **A240**, 599 (1947).
[2] E. C. Stoner, Phil. Mag. **36**, 803 (1945).
[3] J. A. Osborn, Phys. Rev. **67**, 351 (1945).

**B2. Rotational Hysteresis in Alnico and Cunife Magnets.** I. S. JACOBS, *General Electric Research Laboratory.*—Recent work[1,2] has shown that measurement of the rotational hysteresis integral, $R = \int (W_r/I_s) d(1/H)$, may distinctively characterize the magnetization process in permanent magnets. Measurements of $R$ on polycrystalline samples of the precipitation alloy magnets Alnico V, VII, and Cunife yield values between 1.0 and 1.4. If the remagnetizing elements are rod-like, These values indicate a nonuniform magnetization process similar to that in elongated single domain iron. For plate-like elements,[3] comparison with an idealized model continues to indicate a nonuniform process.

[1] C. P. Bean and W. H. Meiklejohn, Bull. Am. Phys. Soc. Ser. II, **1**, 148 (1956).
[2] I. S. Jacobs and F. E. Luborsky, Boston Magnetism Conference (1956). J. Appl. Phys. (to be published).
[3] E. A. Nesbitt and H. J. Williams, J. Appl. Phys. **26**, 1217 (1955).

**B3. Parasitic Ferromagnetism in α Manganese.** H. W. COOPER,* A. ARROTT,† AND H. W. PAXTON, *Carnegie Institute of Technology.*—Arrott, Coles, and Goldman[1] have shown that a parasitic ferromagnetism can be induced at low temperatures in antiferromagnetic[2] $\alpha$ manganese by pickling in nitric acid and that this effect can be subsequently removed by a vacuum anneal. We have confirmed this result. Furthermore we have eliminated as possible sources for this effect the presence of hydrogen or nitrogen in solid solution and the formation of nitrides or hydrides. However, strains arising upon transforming from the $\beta$ phase to the $\alpha$ phase can induce this parasitic ferromagnetism. These results fit well with Li's[3] hypothesis of antiferromagnetic domain boundaries giving rise to parasitic ferromagnetism. According to Li, strains should serve well to stabilize the domain boundaries.

* Present address: Bell Telephone Laboratories, Murray Hill, New Jersey.
† Present address: Ford Motor Company, Dearborn, Michigan.
[1] Arrott, Coles, and Goldman, Phys. Rev. **98**, 1864 (1955).
[2] Shull and Wilkinson, Revs. Modern Phys. **25**, 100 (1953); Kasper and Roberts, Phys. Rev. **101**, 537 (1956).
[3] Y. Li, Phys. Rev. **101**, 1450 (1956).

**B4. Origin and Temperature Dependence of Magnetic Anisotropy in Nonconducting Ferromagnetics.** W. P. WOLF,* *Harvard University* (introduced by J. H. Van Vleck).— The effect of the electrostatic crystalline field has been considered

for a magnetic crystal in which the ions are strongly coupled by ferromagnetic exchange. On the basis of the one ion approximation that the exchange can be represented by a Weiss molecular field it is possible to derive expressions for the anisotropy constants, $K_i(T)$, in terms of the parameters occurring in the spin Hamiltonian of the isolated ions, and the magnetization of the lattice at the temperature, $T$. The treatment assumes that the magnetic electrons can be considered as localized on the individual ions, and thus applies only to nonmetallic substances such as ferrites. The presence of more than one aligned sublattice is easily taken into account if the magnetization of each sublattice can be calculated from the Néel equations. For ions in which there is no orbital angular momentum, or for which it is quenched, only those with $S \geq 2$ will contribute to an over-all cubic anisotropy. In ions such as $Co^{++}$, however, where the orbital momentum is only partially quenched in a cubic field, very high strain dependent anisotropy is predicted. The orders of magnitude to be expected from this model are in good agreement with experiment.

* Supported by U. S. Air Force.

**B5. High-Temperature Electrical Resistivity Measurements of the Ni-Pd Alloy System.** A. I. SCHINDLER, R. J. SMITH, AND E. I. SALKOVITZ, *U. S. Naval Research Laboratory.*—The similarity of Ni and Pd would suggest that the electrical resistivity maximum of Ni-Pd alloys should occur at the 50–50 composition, but measurements[1] at room temperature and below showed a maximum at 70 at %Pd, 30 at %Ni. The shift in the maximum may be explained on the basis of the uneven filling of the two half $d$ bands resulting from the ferromagnetic nature of the alloys.[2] At temperatures where all the alloys are paramagnetic, the two half $d$ bands are equally filled and the resistivity maximum would be expected to occur approximately at the 50–50 composition. To check this, resistivity measurements were made on a series of Ni-Pd alloys from room temperature to 460°C. As one increases the temperature, the maximum in resistivity is found to shift from 70 at %Pd to lower Pd content. At the highest temperatures measured, the maximum does occur at the 50–50 composition as expected. Values of $\partial\rho/\partial T$ are found to be independent of composition over most of the alloy systemat 450°C; a slight decrease is found at the Pd rich end.

[1] Schindler, Smith, and Salkovitz, J. Phys. Chem. Solids **1**, 39 (1956).
[2] A. I. Schindler and A. W. Overhauser, Bull. Am. Phys. Soc. Ser. II, **1**, 344 (1956).

**B6. Electron Structure and Surface Wetting.** N. M. PARIKH AND J. E. GOLDMAN, *Ford Motor Company.*—When a small cube of metal is melted on a solid plaque, the angle of contact that the molten drop forms with the solid surface depends primarily upon the relative surface energies of various interfaces involved. Thus, for a system in which the surface energies of the solid and molten metal are constant at a given temperature, any change in the contact angle will be a measure of the change in the free surface energy of the liquid-solid interface. An attempt has been made to correlate the change in the interfacial energy of a metal carbide interface with the internal electron states in the metal system. Measurements of contact angle were made in nickel-copper and palladium-silver alloys on titanium carbide surface. The results show a very striking decrease in the contact angle to zero in the composition ranges where in the solid state the $d$ band would be nearly but not completely filled. These results suggest a remarkable relation between wetting and the occupancy of the electron $d$ states in transition metal alloys.

**B7. Elastic Constants of Nickel at High Magnetic Fields.** J. R. NEIGHBOURS, G. A. ALERS, AND H. SATO, *Ford Motor Company.*—Slight differences in the elastic constants of ferromagnetic substances depending upon the direction of the magnetic field in the range of saturation magnetization have been observed and interpreted[1] as a "morphic effect." To further investigate this effect, measurements of the wave velocity and attenuation of 10-mc sound waves have been made on a [110] nickel single crystal at fields of 10 000 oe to 20 000 oe. Changes in velocity with direction of magnetization are of the order of 0.1% and are in qualitative agreement with previous measurements. However, polar plots of the velocity as a function of magnetic field direction show a different symmetry from that expected from the ordinary "morphic effect."

[1] W. P. Mason, Phys. Rev. **82**, 715 (1951).

**B8. A Molecular Field Theory for Dilute Magnetic Alloys and the Rare Earth Metals.*** G. W. PRATT, JR., *Lincoln Laboratory.*—In dilute magnetic alloys such as Mn in Cu the magnetic properties must arise from interactions capable of long range effectiveness. Two such are direct exchange between the magnetic atom and conduction electrons which is ferromagnetic and a superexchange interaction between magnetic atoms via the conduction electrons which is antiferromagnetic. A molecular field theory is given based on this model. This leads to the possibility of an antiferromagnetic-ferromagnetic transition. A proof by Smart[1] showing such transitions cannot occur is shown to hold only in very special cases. This molecular field theory applied to Cu-Mn accounts for the antiferromagnetism and shows that direct $s$-$d$ exchange may not be as weak as implied by a previous treatment.[2] The rare earth metals are similar to dilute magnetic alloys since the 4$f$ orbitals on one atom do not overlap those of its neighbors. It is proposed that the magnetic properties of these metals are due to direct and superexchange interactions with conduction electrons. This is supported by the fact that both erbium and dysprosium exhibit an antiferromagnetic-ferromagnetic transition.

* The research reported in this document was supported jointly by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.
[1] J. S. Smart, Revs. Modern Phys. **25**, 327 (1953).
[2] Owen, Browne, Knight, and Kittel, Phys. Rev. **102**, 1501 (1956).

**B9. Antiferromagnetism in Iron-Aluminum Alloys.** A. ARROTT AND H. SATO, *Ford Motor Company.*—As part of an investigation of magnetization and order in the iron aluminum system we have determined the magnetic behavior of an alloy with sufficient aluminum to remove ferromagnetism at any temperature. Magnetic isotherms have been obtained on a specimen with 40 atomic percent aluminum from 2°K to 300°K. The inverse susceptibility is linear with temperature down to 20°K with a slope corresponding to a $g^2S(S+1) = 26 (p_{eff} = 5.1)$ per iron atom and an intercept corresponding to a $\theta$ in the Curie-Weiss law of $-90$°K. The susceptibility remains constant from 20°K to 15°K and then decreases rapidly between 15°K and 2°K. This behavior is rather typical of antiferromagnetic materials. In addition the appearance of a slight remanence which increases rapidly with decreasing temperature below 20°K is also consistent with the behavior of many antiferromagnetic materials below their transition temperatures. If $g$ is approximately two, then the moment indicates a spin state $S = 2$ for the iron atoms in the iron sublattice of the FeAl structure. The moment assigned to the iron atoms in the aluminum sublattice is quite sensitive to the value chosen for $g$ in the iron sublattice. However, for the choice $g = 2$ in the iron sublattice, the spin state of the iron atoms in the aluminum sublattice would be calculated as $S = 5/2$.

**B10. Proposed Model for the Anisotropy in Antiferromagnetic MnO and αMnS.*** W. O'SULLIVAN AND F. KEFFER, *University of Pittsburgh.*—According to Kaplan[1] magnetic dipolar interactions in an antiferromagnetic FCC array with

ordering of the second kind lead to a large anisotropy ($4\times10^6$ ergs/cm$^3$) aligning the spins parallel to ferromagnetic (111) planes; and recent Brookhaven neutron diffraction experiments on MnO, NiO, and $\alpha$MnS confirm this alignment. This large anisotropy, however, disagrees with a much smaller anisotropy estimated by Nagamiya[2] from the field dependence of $\chi_{powder}$ in MnO. Our calculations of some other (weaker) sources of anisotropy possible for $Mn^{++}$ ions in $S$ states suggest a model in which, in addition to Kaplan's (111) plane constraint, a much weaker anisotropy selects preferred directions in those planes. The field dependence of $\chi_{powder}$, as calculated from this model, agrees with experiment if the weak anisotropy is $\sim1.9\times10^4$ ergs/cm$^3$ or possibly less. Furthermore, the presence of this weak anisotropy helps explain the strong spin-resonance absorption, well below the Curie point, observed in powdered MnS and MnO.[3]

* This research was supported by the U. S. Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command under contract No. AF18(600)-892.
[1] J. Kaplan, J. Chem. Phys. **22**, 1709 (1954).
[2] T. Nagamiya, Progr. Theoret. Phys. **6**, 342 (1951).
[3] Okamura, Torizuka, and Kojima, Phys. Rev. **82**, 285 (1951).

**B11. Multispin Axis Structures for Antiferromagnets.** W. L. ROTH, *General Electric Research Laboratory** (introduced by I. S. Jacobs).—The antiferromagnetic structures[1-4] of MnO, CoO, and NiO have generally been deduced from neutron diffraction studies by considering models which assume (1) antiparallel superexchange coupling, and (2) spins parallel and antiparallel to a single crystallographic direction. If only (1) is assumed, multispin axis structures are possible. These are described in the pseudocubic magnetic unit cell by the spin vectors $\mathbf{S}_1$, $\mathbf{S}_2$, $\mathbf{S}_3$, $\mathbf{S}_4$ with position coordinates 000, 1/4 3/4 0, 1/4 0 3/4, 0 3/4 1/4. Several models consistent with the neutron powder diffraction data have been found. One ($\mathbf{S}_1=\mathbf{S}_4=[\bar{1}10]$, $\mathbf{S}_2=\mathbf{S}_3=[\bar{1}01]$) is supported by neutron diffraction from single crystals of NiO; a second ($\mathbf{S}_1=\mathbf{S}_4=[010]$, $\mathbf{S}_2=\mathbf{S}_3=[\bar{1}00]$) is consistent with the tetragonal distortion of CoO. Although multispin axis structures have not been uniquely established relative to the single axis models, they agree equally well with the powder data, and appear superior when single crystal diffraction and crystal symmetry are considered.

* Work performed at Brookhaven National Laboratory Reactor.
[1] Shull, Strauser, and Wollan, Phys. Rev. **83**, 333 (1951).
[2] W. L. Roth, Am. Cryst. Assoc. Meeting, French Lick, Indiana (June, 1956).
[3] Y. Y. Li, Phys. Rev. **100**, 627 (1956).
[4] Goodenough and Loeb, Boston Magnetism Conference (1956).

**B12. Magnetic Analysis of Imperfections in Uranium Oxide.*** J. E. GOLDMAN, *Ford Motor Company*, AND A. ARROTT, *Carnegie Institute of Technology*.†—Magnetic isotherms of uranium oxides containing varying amounts of oxygen from $UO_2$ to $U_3O_8$ have been measured between room temperatures and liquid helium using a method previously described.[1] It has been possible on the basis of these measurements to ascertain that: (1) the additional oxygen goes into the $UO_2$ lattice interstitially rather than by the creation of vacancies in the uranium sublattice; (2) at nonstoichiometric compositions close to but higher than $UO_2$ the charge balance is maintained by replacement of $U^{+4}$ by $U^{+6}$ ions; and (3) the phase limits for low temperature oxidation are $UO_{2.31}$ as the upper limit of the $UO_2$ phase and $UO_{2.44}$ for the lower limit of the $U_3O_8$ phase. The presence of oxygen as interstitials is indicated by an increase in the magnitude of the negative exchange interaction with increasing oxygen content as would be caused by 180° superexchange interactions between $U^{+4}$ ions through the interstitial oxygens. Anomalies are observed below 20°K. In $UO_2$, this appears to be antiferromagnetism. At other compositions, the interpretation of the low temperature behavior is not as clear cut.

* Supported by the U. S. Atomic Energy Commission under subcontract with the Atomic Power Division, Westinghouse Electric Corporation.
† Present address: Ford Motor Company.
[1] A. Arrott and J. E. Goldman, Rev. Sci. Instr. **28**, 99 (1957).

## THURSDAY MORNING AT 10:00

Irvine Auditorium

(B. LAX presiding)

### *Compound Semiconductors*

**C1. Double Refraction of Axial Crystals. I. Wurtzite Structures.*** F. KEFFER, *University of Pittsburgh*.—The Lorentz factor, $4\pi/3$, used in the derivation of the Lorentz-Lorenz formula relating the optical index of refraction of an ionic crystal to the electronic polarizabilities of the ions, assumes (a) no overlap between neighbor ions, and (b) tetrahedral symmetry. In the absence of (b), any difference between the dipole field factors along and perpendicular to the crystal axis may lead to double refraction. Anisotropy in neighbor-ion overlap, which may also cause double refraction, should be absent in wurtzite structures, which have tetrahedral symmetry out to next-nearest neighbors. A revised Lorentz-Lorenz formulation, introducing anisotropic field factors, leads to a pair of equations for the ordinary and extraordinary indices of refraction. Using measured values of the indices one may solve these equations for the electronic polarizabilities of both types of ions. Results for ZnS, ZnO, BeO, CdS, and AgI are in good agreement with the polarizabilities estimated by Tessman, Kahn, and Shockley[1] from self-consistent calculations on simpler ionic crystals. Polarizabilities of the metallic ions tend to be slightly larger than the TKS values, indicating electron displacement towards these ions, a displacement required by the partial covalent bonding.

* This research was supported by the U. S. Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command.
[1] Tessman, Kahn, and Shockley, Phys. Rev. **92**, 890 (1953).

**C2. Double Refraction of Axial Crystals. II. Rutile Structures.*** B. SMILOWITZ AND F. KEFFER, *University of Pittsburgh*.—The theory outlined above for wurtzite structures has been applied to rutile structures. Here, since the nearest neighbors of any ion do not satisfy tetrahedral symmetry, overlap effects will be expected to contribute to double refraction. These effects should be small, however, in strongly ionic crystals. The dipole field factors were calculated for a rutile structure with $c/a=0.67$, and applied to the determination of the electronic polarizabilities of the ions in $MgF_2$ and $SnO_2$. The polarizabilities for $Mg^{++}$ and $F^-$ agree well with those quoted by Tessman, Kahn, and Shockley.[1] The values obtained for $Sn^{4+}$ and $O^{--}$ differ from the TKS values to a greater extent than $Mg^{++}$ and $F^{--}$, indicating, as the elec-

tronegativity values would lead one to expect, a larger degree of overlap for $SnO_2$. Other compounds will be discussed in addition to those mentioned above. We have also used the field factors to evaluate the magnetic dipolar fields at fluorine sites in paramagnetic and antiferromagnetic $MnF_2$.

* This research was supported by the U. S. Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command.
[1] Tessman, Kahn, and Shockley, Phys. Rev. **92**, 890 (1953).

**C3. Preparation of GaAs Single Crystals.** J. M. WHELAN AND G. H. WHEATLEY, *Bell Telephone Laboratories.*—Gremmelmaier has grown GaAs single crystals from the melt, using a crystal puller sealed in a quartz tube in which the vertical motion of the cyrstal is controlled by the motion of an external magnet coupled to the crystal holder.[1] Recently, we have grown single crystals by the floating zone method, which offers the following advantages: (1) minimization of apparatus contamination, (2) the relatively small liquid volume minimizes temperature variations and consequent concentration gradients in the liquid, (3) the relatively large surface to volume ratio of the liquid favors the rate of approach to gas-liquid equilibrium, and (4) the motion of the liquid-solid interface is controlled by a direct mechanical drive. Crystals have been grown under an As pressure of 535±25 mm using zone velocities of 1–2 mm/min. These varied in diameter from 4.5 to 6.8 mm and were up to 19 cm long, the limit of our apparatus. The resistivities varied from $10^{-3}$ to $10^{5}$ ohm cm. Room temperature $\mu_H$, $[(8/3\pi)R\sigma]$, of 4100 and 330 $cm^2$ $volt^{-1}sec^{-1}$ have been observed in $n$ and $p$ type samples containing $2\times10^{16}$ and $2.5\times10^{16}$ carriers $cm^{-3}$, respectively. Lifetimes of 20 $\mu$sec have been measured by photoconductivity decay.

[1] von R. Gremmelmaier, Z. Naturforsch. **11a**, 511–513 (1956).

**C4. Transient Photoconductivity in Pure AgCl at Room Temperature.*** F. C. BROWN, *University of Illinois.*—At room temperature and above, a steady electric field cannot be maintained between blocking electrodes in silver chloride because of ionic conductivity. However photocurrent can be measured using a technique in which a fast rising step voltage is followed by illumination of the crystal with short 0.2 $\mu$sec pulses of light.[1] The method is used to compare the volume photoresponse of various crystals at room temperature and to obtain information on the factors which control electron-hole lifetimes. Results are presented for vacuum grown single crystals of AgCl which contain only a few tenths of a part per million heavy metal impurities. The influence of anneal in various atmospheres and on MgO or CaO is discussed. Electron lifetimes of 0.35 $\mu$sec and longer are directly observed. The ratio of electron range to hole range at high voltages is found to be greater than 150 in some crystals. Assuming equal hole and electron mobilities an upper limit of hole lifetime can be established at about $3\times10^{-9}$ sec.

* Partially supported by the U. S. Air Force.
[1] F. C. Brown, Phys. Rev. **92**, 502 (1953).

**C5. Electrical Properties of the Semiconductors $Mg_2Si$ and $Mg_2Ge$.** R. G. MORRIS, R. D. REDIN, AND G. C. DANIELSON, *Iowa State College.*—Higher-purity single crystals of $Mg_2Si$ and $Mg_2Ge$ have been prepared from melts of stoichiometric proportions of the constituents in graphite crucibles. Measurements of Hall effect and electrical resistivity have been made from 77°K to 1000°K. Carrier concentrations in the saturation region were as low as $8(10)^{16}$ electrons/$cm^3$ in $Mg_2Si$ and $3(10)^{18}$ electrons/$cm^3$ in $Mg_2Ge$. In better agreement with results of Winkler[1] than with those of Whitsett and Danielson,[2] the energy gap obtained from Hall effect data in the intrinsic range was 0.80 ev for $Mg_2Si$ and 0.70 ev for $Mg_2Ge$ Highest Hall mobilities at 300°K were 400 $cm^2$/volt-sec for $Mg_2Si$ and 280 $cm^2$/volt-sec for $Mg_2Ge$. The Hall mobility was found to vary in the intrinsic range as $T^{-a}$ where $2<a<3$ in $Mg_2Si$ and $a=2$ in $Mg_2Ge$. One $p$-type single crystal of $Mg_2Si$ has been obtained by doping with 0.2% by weight of silver.

[1] U. Winkler, Helv. Phys. Acta **28**, 633 (1955).
[2] Whitsett and Danielson, Phys. Rev. **100**, 1261(A) (1955).

**C6. Lifetimes in Magnesium Stannide.*** I. I. SOCHARD AND J. H. BECKER, *National Bureau of Standards.*—Determination of both the photoelectro magnetic effect and photoconductivity under steady state conditions permits a direct evaluation of the electron-hole pair lifetime for optically created carriers.[1] This method has been applied to studies of lifetime as a function of temperature between 350 and 90°K on single crystals of the semiconductor $Mg_2Sn^2$ (extrinsic $n$- and $p$-type concentrations $10^{16}-10^{17}$/cc). Cleaved samples, and those subjected to sandblasting and annealing treatments, have been investigated. Radiation from a Nernst glower (chopped at 3000 cps) and the use of suitable filters allowed determination of the response to various wavelength regions. The responses were linear with applied electric and magnetic fields, and approximately linear with light intensity. Samples with the highest lifetimes followed approximately $\tau\sim\exp\times(-E_g/2kT)$ between 350 and 250°K. For lower temperatures the lifetimes either decreased or remained constant. Below 150°K photovoltaic effects and large "anomalous lifetimes" occurred (not observable by transient decay checks). Bulk electron-hole pair lifetimes at 300°K ranged from $10^{-6}$ to $10^{-7}$ sec.

* Research supported by the Office of Scientific Research, Air Research and Development Command, U. S. Air Force.
[1] W. Van Roosbroeck, Phys. Rev. **101**, 1713 (1956).
[2] Blunt, Frederikse, and Hosler, Phys. Rev. **100**, 663 (1955).

**C7. Energy Transport in Photosemiconductors of the ZnS-CdS Type.** M. BALKANSKI (introduced by A. von Hippel).—When a CdS crystal is irradiated at some point and the rest of the semiconductor is shielded, the excitation travels through the nonirradiated part. A photocurrent can be measured far from the irradiated spot. A new method is used to measure the diffusion constant, diffusion length, and lifetime of the energy carriers. For a very photosensitive crystal of CdS the diffusion constant is $D+100$ $cm^2$/sec, lifetime $\tau=10^{-3}$ sec, and diffusion length $L=(D\tau)^{\frac{1}{2}}=0.3$ cm. The energy is transported by excitons; an electrical field has no influence on the diffusion. When an exciton comes into contact with a crystal defect, (impurity, dislocation, etc.) or reaches the surface, it is dissociated into a free electron and a hole. This work was done in the Fritz Haber Institut (Berlin) by Dr. I. Broser and is still in progress.

**C8. Calculation of the Elastic Shear Constants of the Zincblende Structure.*** D. A. COHEN AND J. R. REITZ, *Case Institute of Technology.*—The total energy of a system of valence electrons and ion cores arranged in the zincblende structure was found to separate into four terms, a Coulomb term, a Fermi energy term, the kinetic energy of the lowest state, and a Coulomb type correction term. The second derivatives of the Coulomb term were calculated using the Ewald method where part of the valence electronic charge was imagined to be concentrated as spherical charges in the "bonds." The Fermi contribution to the elastic constants was calculated after the method of Leigh.[1] The Coulomb correction term may be combined with the Coulomb term by modifying the ionic charges, and the kinetic energy of the lowest state is in the process of being determined. The results of the first two terms show qualitative agreement with experiment (Ge, Si, InSb). The main point to be observed is that the Fermi energy term is required to stabilize the $C_{44}$ elastic constant.

* Work supported by the Office of Naval Research.
[1] R. S. Leigh, Phil. Mag. **42**, 139 (1951).

**C9. Infrared Absorption and Energy Band Structure of Indium Antimonide.*** G. W. GOBELI AND H. Y. FAN, *Purdue University.*—The investigation of the effect of a large carrier concentration on the intrinsic absorption in *n*-type samples has been extended to 90°K and 5°K. At 90°K, the absorption edge, which is shifted to shorter wavelengths, can be correlated with that of pure samples by the expression based on direction transitions, as had been shown for room temperature results.[1] At 5°K, the measured absorption edge is somewhat less steep than predicted by the expression. Measurements have been made at 5°K on degenerate *p*-type samples of various hole concentrations. Instead of showing similar shifts of absorption edge as in *n*-type samples, the absorption behaves quite differently, indicating that the crystal does not have a simple valence band. For medium hole concentrations, the absorption has about the same threshold but does not reach the magnitude observed in pure samples. The spectral curve of absorption coefficient approaches that of pure samples only at shorter wavelengths. For very high hole concentrations, the results indicate a shifting of the threshold. These results bear evidence to the existence of overlapping bands in the valence band.

* Work supported by a Signal Corps contract.
[1] H. Y. Fan and G. W. Gobeli, Bull. Am. Phys. Soc. Ser. II, 1, 111 (1956).

**C10. Piezoresistivity of Indium Antimonide.*** ROY F. POTTER, *National Bureau of Standards.*—The piezoresistivities of "*n*" and "*p*" types InSb have been measured in the temperatures range 77°K to 300°K. The procedure for the measurements was similar to that used by Smith[1] for Ge and Si in that a tensile stress was applied along the sample axis while longitudinal or transverse resistivity was measured. The magnitude of the applied stress was determined by means of a balance beam and the load was changed by increments of 100 g up to 1000 g. Hall voltage measurements indicated that all samples had carrier concentrations at 77°K of the order $10^{15}$/cm³. The results at 77°K for "*n*" type samples show that the elastoresistivity coefficients have a very small magnitude. This is in agreement with the expectations that the minimum of the conduction band lies at (0,0,0) in *k* space. Measurements on "*p*" type material give results at 77°K that are very similar to those for "*p*" type Ge and Si. The volume effect is small while the coefficient $M_{44}$ is large in comparison. The other principal coefficient $(M_{11}-M_{12})/2$ is also large in magnitude compared to the volume effect, which differs from the results given for Ge and Si.

* Research supported by Office of Scientific Research, Research Development Command, U. S. Air Force.
[1] C. S. Smith Phys. Rev. **94**, 42 (1954).

**C11. Optical Absorption in HgSe.** DAVID REDFIELD, *National Carbon Research Laboratories.*—Optical absorption measurements have been made on single crystals of HgSe grown by deposition from the vapor. Chemical analysis places a maximum deviation from stoichiometry of these crystals at a few tenths of 1%. Several crystals polished to thickness of 0.12 mm to 0.25 mm were measured in the spectral range 0.8 $\mu$ to 15 $\mu$. No transmission was observed in this range, and an estimated minimum absorption coefficient of 430 cm$^{-1}$ has been assigned at 5$\mu$. This absence of a fundamental absorption edge conflicts with the values for the energy gap estimated by Goodman[1] as 0.7 ev and tabulated by Winkler[2] as ~1 ev, but confirms the results of Blum and Regel[3] on nonstoichiometric samples. Hall effect and resistivity measurements on one of our crystals between 77°K and 300°K show a degenerate temperature dependence with $2\times10^{18}$ free electrons per cm³ and a carrier mobility of 4000 cm²/v-sec at room temperature.

[1] C. H. L. Goodman, Proc. Phys. Soc. (London) **B67**, 258 (1954).
[2] U. Winkler, Helv. Phys. Acta. **28**, 633 (1955).
[3] A. I. Blum and A. R. Regel, J. Tekh. Fis. (U.S.S.R.) **21**, 316 (1951).

## *Invited Paper*

**C12. Electron, Hole, and Ion Motion in CdS Crystals.** R. W. SMITH, *RCA Laboratories.* (30 min.)

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THURSDAY MORNING AT 10:00

Physical Sciences, Room A-2

(S. L. QUIMBY presiding)

## *Metals and Alloys*

**CA1. The Elastic Constants of Zinc.** G. A. ALERS AND J. R. NEIGHBOURS, *Ford Motor Company.*—Of interest, in comparison of theories of metallic binding and of lattice vibrations, are the crystal elastic constants. These have been measured for crystalline zinc through the solid range from 4.2°K to near the melting point using the pulsed ultrasonic method. The temperature variation of the constants is about the same as for other metals. As the melting point is approached the shear constants $1/2(C_{11}-C_{12})$ and $C_{44}$ do not vanish or show very rapid temperature variations. The room temperature values of the constants are substantially in agreement with the results given by Wert and Tyndall.[1]

[1] C. A. Wert and E. P. T. Tyndall, J. Appl. Phys. **20**, 587 (1949).

**CA2. The Elastic Constants of Indium.*** D. R. WINDER AND CHARLES S. SMITH, *Case Institute of Technology.*—The elastic constants of tetragonal indium have been measured by the ultrasonic pulse echo method. Three single crystals were cut so that pulses propagated in the approximate directions [100], [110], and [011], respectively. The nine wave velocities allow the six constants to be determined with three internal checks. If indium is regarded as a tetragonally deformed fcc structure the constants may be referred to axes coincident with the deformed cubic axes. Preliminary results are consistent with the small tetragonality. For the longitudinal constants $C_{11}>C_{33}$. The shear constants are exceptionally small compared with the longitudinal constants and are in the order $C_{66}>C_{44}>(C_{11}-C_{12})/2>(C_{11}+2C_{33}+C_{12}-4C_{13})/6$. The last constant measures the stiffness to a strain which changes the $c/a$ ratio at constant volume.

* Work supported by the Office of Naval Research and the National Carbon Company.

**CA3. Choice of Functional Dependence of Ordering Energy on Long-Range Order.** JEROME ROTHSTEIN, *Signal Corps Engineering Laboratories.*—If $T_c$ is a singularity for dependence of long-range order $S$ or ordering energy $V$ on temperature,

there is no reason to believe an expansion of $V(S)$ about $S=0$ has any validity. We choose to expand about $S=1$, where good behavior of $V(S)$ is most likely. Writing $V(S)=V_0-\Sigma V_m \times(1-S)^m$, the Bragg-Williams approximation (BW) is then $V_0=V_1$, other $V_m$ zero. More generally, $V(0)=0$ if and only if $V_0=\Sigma V_m$. If this special assumption is not made $V(S)$ can vanish for $S=S_e>0$. Taking $V=0=V(S_e)$ at $T_e$, this implies a sharper drop in $V$ at $T_e$ than BW, permits discontinuous drop in $S$ at $T_e$ (cf $Cu_3Au$), and thus a permitted $S$ range $0\leqslant S\leqslant S_e$ for $T\geqslant T_e$; $S=0$ is preferred for $T>T_e$ for statistical reasons. Disordered material quenched to $T<T_e$ then premits slightly more natural motivation for nucleation and growth of order by fluctuations in $S$ than does $V(0)=0$. Several simple one and two parameter approximations are discussed. The natural first approximation near $S=1$ is $V=V_0$, which has led to good agreement[1] with resistivity relaxation data of Burns and Quimby[2] for ordered $Cu_3Au$ below $T_e$.

[1] J. Rothstein, Phys. Rev. **94**, 1429(A) (1954).
[2] F. Burns and S. L. Quimby, Phys. Rev. **94**, 1429(A) (1954); **97**, 1567 (1955).

**CA4. Ordering Kinetics in Long-Range Ordered $Cu_3Au$.** A. S. Nowick,* R. Feder, and M. Mooney, *Frankford Arsenal.*—The change in order of an already long-range ordered sample, which accompanies a change in temperature below the critical temperature, is one of the simplest of solid-state reactions since it takes place homogeneously rather than through nucleation. Dienes[1] has proposed a theory for the kinetics of such a process, which under suitable approximations may be reduced to a simple second-order differential equation whose solutions are the hyperbolic functions first proposed by Rothstein.[2] Measurements have been made of the change in lattice parameter with annealing in the range 210–290°C of specimens originally brought to equilibrium at 370°C and then quenched. The kinetic curves may be fitted to Rothstein's equation and the rate constant $\alpha$ obtained as a function of annealing temperature. When the results of the present measurements are combined with those of Weisberg and Quimby (unpublished) it is found that the plot of $\log\alpha$ *vs* $1/T$ gives an excellent straight line with an activation energy of 2.03 ev and a frequency factor of $10^{14.6}$ sec.

* Permanent address: Yale University.
[1] G. J. Dienes, Acta Metallurgica **3**, 549 (1955).
[2] J. Rothstein, Phys. Rev. **94**, 1429(A) (1954).

**CA5. Ordering in Alloys of Mg and Cd by Means of Internal Friction.** J. Enrietto and C. Wert, *University of Illinois.*—Further application of internal friction methods to determination of ordering in Mg-Cd alloys has been attempted. Measurements have been made for compositions from 25 atomic percent Mg to 50%. The minimum in the internal friction at 25% Mg reported earlier has been confirmed; this corresponds to existence of order in $MgCd_3$. The internal friction increases from 25% Mg to a maximum at 30%, where it dips sharply to a minimum at 31% Mg. After another sharp rise to a maximum at 33% Mg, there is a slow decrease to zero at the ideal ordering composition MgCd. Except for the minimum at 31% Mg, the data can be explained on the basis of facts already known about this alloy system. The region about 31% has been long in dispute; the literature contains a number of claims for and against the existence of a compound here. The present measurements show that there is a strong increase in short-range order (or perhaps even another ordered structure) at this point. No evidence of the presence of oxides was observed, nor did the samples oxidize readily at room temperature as has been reported for these alloys.

**CA6. Internal Friction in Fe-Al Alloys.*** D. B. Fischbach, *California Institute of Technology.*—Internal friction measurements have been made on 0.045 in. diam cast wires of nominal composition Fe−8 wt percent Al. Measurements were made over the range from 20° to 800°C in a He atmosphere with an enclosed torsion pendulum apparatus. A longitudinal magnetic field of ~500 oe could be applied to the specimen. The damping spectrum of this alloy is dominated by magnetic contributions, both amplitude dependent and independent. The magnetic damping, measured at constant amplitude, goes through a minimum near 450°C, then rises to a broad peak near 600°C before vanishing at the Curie point (~725°C). Both magnetic contributions disappear in a magnetic field. The amplitude dependent component varies linearly with maximum surface strain amplitude, $\epsilon$, at least for $2.7\leqslant\epsilon\leqslant 13\times10^{-6}$, and is therefore attributed to magnetoelastic static hysteresis. Measurements in a magnetic field reveal a non-magnetic peak, located at 545°C at a frequency of 1.2 cps. This peak is amplitude-independent and of correct width for a single relaxation time anelastic peak. The activation energy is ~58 000 cal/mole and the relaxation strength $\sim1.15\times10^{-2}$. This peak is believed to be due to stress-induced ordering. The grain boundary peak is located above 800°C.

* Supported by Department of the Army, Ordnance Corps.

**CA7. Extent of the Austenite-Martensite Transformation in Pure Iron-Carbon Alloys.** D. P. Koistinen and R. E. Marburger, *General Motors Corporation* (introduced by G. M. Rassweiler).—Upon quenching a solid solution of carbon in gamma iron (austenite) to temperatures lower than a certain temperature $M_s$ (which is known to be a function of the amount of carbon dissolved) a diffusionless nonequilibrium transformation of the face-centered cubic phase to a metastable body-centered tetragonal phase (martensite) occurs. Quantitative x-ray diffraction data will be presented which establish a new general equation for the fraction of austenite remaining untransformed at any temperature $T_q$ below $M_s$ in pure iron-carbon alloys in the range from 0.4 to 1.2% carbon. This equation $V_\gamma=\exp[-(1.13\times10^{-2})(M_s-T_q)]$, $T_q\leq M_s$ (where $V_\gamma$ represents the untransformed fraction of the gamma phase) is similar to an equation proposed by earlier investigators in that it is a function of $M_s$ and $T_q$ only. In addition to being somewhat simpler, however, this new equation prescribes that at any temperature below $M_s$, a constant fraction of the remaining gamma phase is transformed per unit decrement in temperature. The implications of this result will be discussed. Additional data will be presented which demonstrate the applicability of this equation to steels containing other alloying elements besides carbon.

**CA8. Precipitation of C in α Iron.** D. Keefer and C. Wert, *University of Illinois.*—The solubility of C in $\alpha$ iron in equilibrium with cementite has been established previously by both chemical analysis and internal friction techniques. The latter method depends on the fact that the internal friction is proportional to the amount of dissolved C present; the internal friction will therefore stabilize itself at a level proportional to the solubility of C at the temperature at which the specimen is held. In the past it has been common to approach this equilibrium from the "high" side; i.e., from an excess of dissolved C. This method has the defect that a long time is required for equilibrium to be reached and one never knows that true equilibrium has been reached. The present experiment reports an attempt to remedy this; equilibrium is approached from both sides. Measurements where equilibrium was approached from the high side agree with those reported earlier. In measurements from the low side an unexpected event was seen; instead of a smooth rise from below to the equilibrium value, overshooting occurred. After overshooting, the internal friction decreased to the proper value. The overshooting is thought to be reversion; the redissolving of particles of precipitate too small to be stable at the holding tempearture.

**CA9. Kinetics of Vacancy Precipitation in a Ag-Zn Alloy.*** A. E. Roswell† and A. S. Nowick, *Yale University.*—By means of anelastic relaxation measurements it is possible to

observe the rate at which vacancies, quenched into a Ag-Zn solid solution from 400°C, anneal out at relatively low temperatures.[1] The kinetics of the early stage of vacancy precipitation are observed to follow a general law of the form: $w=1-\exp(-at^m)$, where $w$ is the fraction of vacancies precipitated and $m$ is called the "growth exponent." When the alloy is well annealed before quenching-in of the vacancies it is found that $m=2$. This growth exponent is interpreted to mean that vacancies condense into disks with radius increasing proportionally to the time and with a constant thickness (presumably one atom spacing). When the alloy is cold-worked (by 1 to 5%) either before or after quenching, the data may be fitted with a growth exponent of 2/3. This value is characteristic of point defects migrating to dislocations under an interaction energy which varies as the inverse first power of the distance.[2] The dislocation density calculated from the present data for a sample cold-worked 5% is close to $10^{11}/cm^2$.

* Work supported by the Office of Ordnance Research.
† Now at the Brookhaven National Laboratory.
[1] A. E. Roswell and A. S. Nowick, J. Metals **5**, 1259 (1953).
[2] A. H. Cottrell and B. A. Bilby, Proc. Phys. Soc. (London) **A62**, 49 (1949).

**CA10. Anisotropy of the Anelastic Relaxation Strength in Silver-Zinc Solid Solutions.*** D. P. SERAPHIM AND A. S. NOWICK, *Yale University*.—The dependence of the magnitude of the internal friction peak in single crystals of Ag–Zn alloys on orientation was studied both in flexural and in torsional vibration. The alloys ranged in composition from 25 to 27 atomic percent Zn. The formal theory of this phenomenon[1] predicts a straight line when the product of relaxation strength and the appropriate elastic constant is plotted against the orientation function $\phi=\alpha_1^2\alpha_2^2+\alpha_1^2\alpha_3^2+\alpha_2^2\alpha_3^2$ where the $\alpha$'s are direction cosines of the specimen axis with respect to the cubic axes. The present experiments confirm this relation. If we define $R$ as the ratio of peak height in the ⟨111⟩ to that in the ⟨100⟩ orientation, the results show that $R$ is approximately 6.0 in torsion and 0.16 in flexure for this alloy. This result is in disagreement with the ratio 1.7 predicted by LeClaire and Lomer[2] for torsion from their theory of stress-induced local ordering, and implies that this theory must be modified.

* Work supported by the Office of Ordnance Research.
[1] C. Zener, *Elasticity and Anelasticity of Metals* (University of Chicago Press, Chicago, 1948), p. 57.
[2] A. D. LeClaire and W. M. Lomer, Acta Metallurgica **2**, 731 (1954).

**CA11. Precipitated Phases and Their Distribution in an Al-Si-Cd Alloy.** R. E. MARBURGER AND A. W. SCHLUCHTER, *General Motors Corporation* (introduced by G. M. Rassweiler).—The composition and distribution of the precipitated phases in an Al–4% Si–1% Cd alloy as a function of thermal history have been studied utilizing x-ray and electron diffraction and electron microscopy. Thin silicon crystallites less than 1 micron in size are detected in aluminum-oxide replicas and carbon-extraction[1] replicas of specimens tempered above 400°F and have been identified by "selected-area" electron diffraction. In carbon extraction replicas, the silicon remaining undissolved after solution treatment at 1000°F can be easily distinguished from that precipitated upon tempering. The amount of silicon observed to dissolve and reprecipitate is in agreement with equilibrium data. The extent of precipitation as a function of thermal history has been established and followed by quantitative measurements of x-ray diffraction line intensities on the series of samples studied. The cadmium phase has been detected and identified by electron metallographic comparison of aluminum-cadmium, aluminum-silicon, and aluminum-silicon-cadmium alloys. The amount of the precipitated silicon phase of a specific type in the ternary alloy can be correlated with mechanical performance of the alloy.

[1] R. M. Fisher, "Electron microstructure by 'extraction replica' technique," ASTM Publication No. 155.

**CA12. Diffusion in Silver-Cadmium and Silver-Indium Alloys.** A. H. SCHOEN, *University of Illinois*.—Tracer diffusion measurements have been made for each component of the binary alloys silver-cadmium and silver-indium, throughout the range of the silver-rich primary solid solutions. Three different compositions were studied for each of the two systems, over a range of temperature between 450°C and 950°C. The diffusion coefficients were all observed to increase with increasing solute composition, with a corresponding monotonic decrease in the activation energies. The composition dependence of the diffusion coefficients is compared with extrapolations of present theory, particularly with respect to size effect, relative valence, and melting point.

**CA13. Impurity Diffusion in Copper.*** C. T. TOMIZUKA, *University of Chicago*.—In order to study the effect of the atomic size of diffusing elements on the impurity diffusion rate' diffusion of silver and gold in single crystals of copper was measured. While gold atoms expand the copper lattice approximately 30% more effectively than silver atoms do, the diffusion rate of silver in copper was found to be 4 times faster than that of gold. The results can be expressed as $D=0.69\exp(-49\,700/RT)$ cm²/sec and $D=0.23\exp(-44\,000/RT)$ cm²/sec for the diffusion in copper of gold and of silver, respectively. Preliminary results on the diffusion of electropositive elements in copper will be reported.

* Supported in part by the U. S. Air Force. The earlier part of this work was carried out at the University of Illinois and was supported in part by the U. S. Atomic Energy Commission.

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## THURSDAY MORNING AT 9:30

## Physical Sciences, Room A-1

(A. M. BUECHE presiding)

### *High-Polymer Physics, I*

### *Invited Paper*

**D1. Volume Viscosity in Liquids.** T. A. LITOVITZ, *Catholic University and Naval Ordnance Laboratory*. (45 min.)

### *Contributed Papers*

**D2. Glass Transition Temperatures of Copolymers.** LAWRENCE A. WOOD, *National Bureau of Standards*.—The glass transition temperature $\theta$ of a copolymer is found to be intermediate between $\theta_1$ and $\theta_2$, the glass transition temperatures of the respective homopolymers. Gordon and Taylor[1] have derived a relation equivalent to $A_1\varphi_1(\theta-\theta_1)+A_2\varphi_2(\theta-\theta_2)=0$,

where $c_1$ and $c_2$ are the weight fractions of the constituents and $A_1$ and $A_2$ are constants. The present work describes methods for determining the validity of the equation. No instance has been found where this form of relation systematically fails to represent the available data. The value of $k = A_2/A_1$ obtained, however, is usually appreciably lower than the ratio of the differences of volume-temperature coefficients above and below the glass transition for each of the homopolymers, as required in the derivation. Fox and Mandelkern from free volume considerations have derived the same equation with the coefficient $k$ having a different physical significance. Published data yield values of $R = k\theta_2/\theta_1$ as low as 0.56 (vinylidene fluoride-chlorotrifluoroethylene copolymer) and as high as 1.8 (ethylene glycol monomethacrylate monoisobutyrate-methyl methacrylate copolymer). Values between 0.8 and 1.2 are common in acrylate copolymers and values near 1.0 are obtained for several systems, including the butadiene-styrene copolymers.

[1] Gordon and Taylor, J. Appl. Chem. **2**, 493 (1952).

**D3. Nature of the Glass Transition.** E. A. Di Marzio and J. H. Gibbs, *American Viscose Corporation.*—The thermodynamic properties of a bulk phase of semiflexible polymeric chains are obtained by consideration of a canonical ensemble of such phases, *in vacuo*, in which the chains of each phase are assumed to fit on a lattice.[1] The mean number of vacant sites is determined as a function of intermolecular energy and temperature. Each molecular chain conformation, $i$, is assigned an energy $E_i$. A second-order transition is predicted and is tentatively related to the glass transition.[2] As special cases, polymeric chains whose flex energies are determined by (1) nearest intramolecular neighbors[1] and (2) both nearest and next nearest intramolecular neighbors are discussed. The calculated dependences of glass temperature on molecular weight and specific heat and thermal expansion coefficient on temperature are in reasonably good agreement with experimental results even for case (1). Allowance for the influence of chain conformation on intramolecular vibrational eigenstates considerably improves this agreement. Copolymers of various types, polymer-polymer solutions, and polymer-monomer solutions are also discussed.

[1] P. J. Flory, Proc. Roy. Soc. (London) **A234**, 60 (1956).
[2] J. H. Gibbs, J. Chem. Phys. **25**, 185 (1956).

**D4. Diffusion in Ethylene Polymers. Desorption Kinetics for a Thin Slab.** D. W. McCall, *Bell Telephone Laboratories.*—Theory and experiments are described for the determination of diffusion coefficients of liquids in solids from desorption data. Experimentally the desorption is followed by weighing the solid specimens. The mathematical process of extracting diffusion coefficients from desorption data is examined and a numerical procedure is described which may be employed in systems in which the diffusion coefficient is concentration dependent. Data and analysis are presented for the diffusion of benzene and *n*-hexane in two ethylene polymers. The two polymers are representative of highly branched high pressure material and low pressure highly crystalline material. A discussion of the molecular significance of the results is given. The desorption curves obtained by numerical analysis are applicable to other systems which exhibit a similar dependence of the diffusion coefficient upon concentration.

**D5. Simple Technique for Measuring the Roughness and Hardness of Plastics.** A. J. G. Allan, *du Pont Experimental Station.*—The profile of the contact area produced when a glass lens is pressed on to a soft plastic is a convenient way to study the surface roughness. Analogous to the taper sectioning of metals, the technique is more convenient for soft plastic materials and is easily adapted to the measurement of hardness. Application of this compression profile technique to a study of roughness of polyethylene film shows that the extremes of optical defect are probably due to two types of roughness. Haze or lack of contrast is caused by a fine, high angle roughness while object distortion is caused by an extremely broad, shallow undulation frequently less than 0.1° angle. The relative proportions of each roughness determine the "clarity" of the film.

**D6. Optical Studies of Crazed Plastics Surfaces.** Sanford B. Newman and Irvin Wolock.—Optical studies were made of crazed plastics surfaces, principally those of cast polymethyl methacrylate. The techniques used for these studies were multiple-beam interferometry and light and electron microscopy. The dimensions of the craze cracks produced by short-time stress crazing and by stress-solvent crazing were determined by the above techniques. The craze cracks did not appear to approach dimensions unresolvable by the electron microscope, but instead appeared to have a minimum crack length. An elevation of the surface in the vicinity of a craze cracks was observed. Some crazed specimens in which the crazing had apparently "recovered" when viewed with the unaided eye still exhibited the surface displacement typical of crazed specimens. Flow lines were observed in some crazed specimens of polymethyl methacrylate, emanating from the ends of craze cracks.

**D7. Mechanical Behavior of Plastics.** I. J. Gruntfest,* E. M. Young, Jr., and Walter Kooch, *Rohm and Haas Company.*—The applicability of Nutting's equation to the mechanical behavior of some soft plasticized polyvinyl chloride preparations noted by Dyson in creep experiments is further demonstrated by force-length measurements at constant rate of strain. This suggests new criteria for the characterization of soft plasticized PVC. For example, in a stretching experiment in which the sample is subjected to a strain $(L-1)$ which increases linearly with time $(t)$ at the rate $(R)$, the definition of "modulus" as the limit at small strains of the ratio of the force $(F)$ to the strain is clearly inappropriate. That is, when

$$L-1 = GF^m t^n,$$

$$\lim_{L-1 \to 0} \left(\frac{F}{L-1}\right) = (L-1)^{\frac{1-n-m}{m}} R^{n/m} G^{-1/m},$$

which may be zero or infinite and also depends on the strain rate. Some even more general force-length-time relationships for plastic are discussed which have been found useful for predicting the conditions of tensile failure. More complicated relationships of particular interest provide for the possibility of force-time superposition of creep curves. Published creep data are considered from this point of view.

* Present address: General Electric Company, Philadelphia.

**D8. High Speed Stress-Strain Machine.** R. D. Spangler, *E. I. du Pont de Nemours and Company.*—A machine has been designed and built to test plastics at a very high rate of straining. While a rate of straining of 120 000 %/sec is achieved, impact loading is avoided by a damping system which constrains the machine to rise exponentially to a constant velocity. The machine is pneumatically driven and has adequate energy so that it does not slow down due to sample loading. Force is measured by a piezoelectric gauge and recorded on a Polaroid Camera. Fracture phenomena are studied with the aid of a rotating mirror camera.

**D9. Tensile Properties of Plastics and Their Dependence on the Rate of Strain.** W. Wilfried Brandt and R. D. Spangler, *du Pont Experimental Station.*—Tensile strengths and ultimate elongations at high rates of strain have been obtained for a number of commercial and experimental high

polymers. The behavior at high rates of strain (ca $7\times10^6$ %/min) was contrasted with behavior at low rates (down to 3%/min). In general the high rate tensile properties are found to be quite different from those obtained at low rates of strain. The correlations of tensile strengths and ultimate elongations with other physical properties are discussed and possible extensions are indicated.

**D10. Morphology of Fractures in Polymethyl Methacrylate.** W. F. BUSSE, *E. I. du Pont de Nemours and Company, Inc.*, AND E. OROWAN AND J. E. NEIMARK, *MIT.*—The catastrophic failure of rigid high polymers by fracture under tensile stresses leads to the development of characteristic patterns in the fracture surfaces. We know these patterns vary with the speed of crack travel, but we do not know much about the mechanisms by which the different types of patterns are formed. Measurements of the speed of crack propagation in large (2-ft wide×6-ft long) samples of polymethyl methacrylate by two of the authors (E. Orowan and J. E. Niemark) gave some unusual examples of fracture surfaces. Because the speed of crack travel increased slowly in these samples, the different types of fracture patterns were well separated and some new effects were observed, including several orders of spectral colors when the surface was viewed by reflected light. Photographs of these patterns will be shown and possible mechanisms of their formation will be discussed.

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THURSDAY AFTERNOON AT 2:00

Physical Sciences, Room A-1

(C. F. HAMMER presiding)

## *High-Polymer Physics, II*

### *Invited Paper*

**E1. The Nuclear Magnetic Resonance of Polymers.** R. L. MILLER, *Monsanto Chemical Company.* (30 min.)

### *Contributed Papers*

**E2. Molecular Motion in Polyethylene.** W. P. SLICHTER AND D. W. MCCALL, *Bell Telephone Laboratories.*—Molecular motion has been studied in a highly-branched polyethylene, DYNK, and in a linear polyethylene, Marlex 50. The studies involved the use of nuclear magnetic resonance spectroscopy over a temperature range of 80°K to 410°K. It is shown that crystallinity in the linear polyethylene persists to within a few degrees of the "melting point" of the gross polymer, and that chain torsion within the crystallites is comparatively restricted until shortly below this temperature. On the other hand, chain torsion within the crystallites of the branched polyethylene is much freer, presumably due to the presence of lattice defects, conceivably from the incorporation of branch points into the crystallites. Crystallinity in the branched polyethylene disappears at much lower temperatures than in the linear polymer. There is considerable motion of chain segments within the amorphous regions of both polyethylenes although at a given temperature the linear polymer exhibits more constraint than does the branched polymer. The amorphous portions of both polymers possess attributes of a viscous liquid, even at temperatures well below the melting point of the gross material. Activation energies and frequency factors for the motions of chain segments in the amorphous portions have been computed.

**E3. Nuclear Magnetic Resonance and Crystallinity in Polyethylene and Nylon.** N. FUSCHILLO and J. A. SAUER, *The Pennsylvania State University.*—Nuclear magnetic resonance lines have been obtained in samples of polyethylene and nylon over a broad temperature range. Over much of this range it is possible to resolve (somewhat arbitrarily) the observed complex line shape into a broad-line component and a narrow line component. Using the method suggested by Wilson and Pake, one can then estimate the crystallinity content. The estimated "NMR crystallinity" is found to differ considerably, over most of the temperature range, from values determined by x-ray methods. It is suggested that rather than provide an accurate estimate of crystallinity content, the proposed procedure gives a useful index of the high frequency rigidity of the sample. Measurements made on irradiated polymers confirm these observations. For example a high index of rigidity is still found, because of the restrictive effect of numerous cross links, even at irradiation doses known to reduce the crystallinity content almost to zero.

**E4. Dynamic Mechanical Properties of Poly-*n*-hexyl Methacrylate.*** WILLIAM C. CHILD, JR., AND JOHN D. FERRY, *University of Wisconsin.*—Values of complex shear compliance ($J'-iJ''$) have been obtained for a fraction of poly-*n*-hexyl methacrylate of weight-average molecular weight $4.19\times10^6$, prepared by Picatinny Arsenal, at 23 temperatures from 5° to 125°C and at frequencies between 15 and 2400 cps, with the Fitzgerald transducer apparatus. The range of $J'$ was from $1.33\times10^{-6}$ to $3.1\times10^{-10}$ cm²/dyne, covering the transition from rubber-like to glass-like consistency. When reduced to 100° by the method of reduced variables, all data superpose to form single composite curves for $J'$ and $J''$, except for two anomalies: a small increase in the maximum value of $J''$ with increasing temperature, and a separation of $J'$ values at different temperatures near the bottom of the dispersion region. The latter can be analyzed in terms of a $\beta$ mechanism, attributable to side chain motions, whose temperature dependence corresponds to an apparent activation energy of 13 kcal. The temperature dependence of the principal, or $\alpha$ mechanism, follows an equation of the WLF form, with $f_g=0.0245$ and $\alpha_f=1.9\times10^{-4}$ deg$^{-1}$. The retardation and relaxation spectra are similar in shape to those of poly-*n*-butyl methacrylate. The logarithm of the monomeric friction coefficient is −5.24 at 100°C and 2.60 at the glass transition temperature.

* Supported by the Ordnance Corps, Department of the Army.

**E5. Dynamic Mechanical Properties of Poly-*n*-octyl Methacrylate.*** WALTER DANNHAUSER, WILLIAM C. CHILD, JR., AND JOHN D. FERRY, *University of Wisconsin.*—Values of

complex shear compliance ($J'-iJ''$) have been obtained for a fraction of poly-*n*-octyl methacrylate of weight-average molecular weight $3.62\times10^6$, prepared by Picatinny Arsenal, at 24 temperatures from $-14°$ to 130°C and at frequencies between 15 and 2400 cps, with the Fitzgerald transducer apparatus. The range of $J'$ was from $2.66\times10^{-8}$ to $3.1\times10^{-10}$ cm²/dyne, covering the transition from rubber-like to glass-like consistency. When reduced to 100° by the method of reduced variables, all data superpose to form single composite curves for $J'$ and $J''$, except for an anomaly in $J''$ at high reduced frequencies; a minimum appear which shifts to higher reduced frequency with decreasing temperature. This is probably caused by a $\beta$ mechanism whose temperature dependence is less than that of the principal or $\alpha$ mechanism. The latter follows an equation of the WLF form. The retardation and relaxation spectra resemble in shape those for other methacrylate polymers. The heights of the maxima in these two spectra increase and decrease, respectively, with increasing length of the polymer side chains.

* Supported by the Ordnance Corps, Department of the Army, and Esso Research and Engineering Company.

**E6. Dynamic Mechanical Properties of a Cellulose Nitrate Gel.*** D. J. PLAZEK AND JOHN D. FERRY, *University of Wisconsin.*—Values of complex shear compliance ($J'-iJ''$) have been obtained for a 23% solution in diethyl phthalate of a sample of cellulose nitrate containing 12.6% nitrogen, intrinsic viscosity 3.70 dl/g. The temperature and frequency ranges were $-47°$ to 35°C and 10 to 2800 cps, respectively. Below 5° the system was a gel, presumably cross-linked by crystallites. The extremes of $J'$ were $2.4\times10^{-8}$ and $9.8\times10^{-10}$ cm²/dyne, spanning most of the transition from rubber-like to glass-like consistency. Above the gel temperature, $J'$ and $J''$ could be superposed to form single composite curves by the method of reduced variables, with shift factors $a_T$ calculated from an equation of the WLF form. Below the gel temperature, there were small deviations corresponding to a progressive change in the retardation spectrum $L$ with decreasing temperature, attributable to increased cross-linking. The maximum in $L$, determined above the gel temperature, is about $3\times10^{-7}$ cm²/dyne and is unusually broad.

* Supported by the Office of Naval Research and Allegany Ballistics Laboratory.

**E7. Effect of Irradiation on the Dynamic Mechanical Properties of Nylon.** C. W. DEELEY, A. E. WOODWARD, AND J. A. SAUER, *The Pennsylvania State University.*—Measurements of elastic modulus and mechanical loss at audio-frequencies have been obtained on irradiated and nonirradiated specimens of polyhexamethylene adipamide over a broad temperature range extending from 80°K to 600°K. The irradiations were carried out at the Brookhaven and Penn State Reactors. The internal friction spectrum of unirradiated nylon 6–6 contains at least four peaks corresponding to different mechanisms being invoked as the temperature is raised. Upon irradiation doses from $0.3\times10^{18}$ nvt to $5.5\times10^{18}$ nvt, significant changes in the dispersion regions occur. At temperatures above the main softening region, an increase in modulus with temperature is found. This is evidence of rubber-like behavior and is accounted for by the introduction of cross-links resulting from ionization and free radical formation produced by the irradiation. At high irradiation doses the percent cross-linking appears to become independent of dose. The various effects found are discussed in terms of molecular forces and mobility of chain segments.

**E8. Mechanical Resonance Dispersion in Polymers at Audio-Frequencies.** EDWIN R. FITZGERALD, *Pennsylvania State University.*—A new type of mechanical dispersion has been discovered in polytetrafluoroethylene and other crystalline polymers. Values of the imaginary part of the complex shear compliance ($J''$) are found to have sharply defined maxima at certain frequencies in the range from 25 to 5000 cps; values of the real part of the complex shear compliance ($J'$) rise to a maximum and then pass through a minimum as a narrow (50 to 100 cps wide) dispersion region is traversed in the direction of increasing frequency. The shapes of the complex compliance *vs* frequency curves are thus similar to those found for the variation of the complex index of refraction with frequency (in absorption bands) at infrared and optical frequencies. The results indicate the presence of a dispersion mechanism different from those giving rise to the usual relaxation dispersion observed in connection with the mechanical properties of polymers. The magnitudes of the mechanical loss maxima and the frequencies at which the effect is observed depend on the static stress history and state of the sample material. This leads to speculation that stressed amorphous regions or other internal stress concentrations may be important in producing this type of dispersion. At present, however, there is no satisfactory explanation for these phenomena. Measurements of the complex shear compliance were made as a function of normal static stress, temperature, and frequency using the electromagnetic transducer method of Fitzgerald and Ferry.

## *Business Session of the Division of High-Polymer Session*

(To be held during Session E at whatever time the Chairman desires.)

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THURSDAY AFTERNOON AT 2:00

Irvine Auditorium

(E. N. ADAMS presiding)

## *DSSP Symposium on High Magnetic Field Effects in Metals and Semiconductors*

**F1. Magneto-Oscillatory Effects in Metals.** M. C. STEELE, *RCA Laboratories.* (30 min.)

**F2. Hall Effect in Very Strong Magnetic Fields.** J. A. SWANSON, *IBM Research Laboratory.* (20 min.)

**F3. Cyclotron-Resonance Experiments on Metallic Bismuth and Graphite.** J. K. GALT, *Bell Telephone Laboratories.* (30 min.)

**F4. Infrared Cyclotron Resonance in Semiconductors and Semimetals.** R. J. KEYES, *Lincoln Laboratory.* (20 min.)

**F5. Interband Magneto-Optic (IMO) Effects in Semiconductors.** E. BURSTEIN, *U. S. Naval Research Laboratory.* (20 min.)

THURSDAY AFTERNOON AT 2:00

Museum Auditorium

(P. W. ANDERSON presiding)

## *Structure of Ferroelectric and Magnetic Materials; Magnetic Resonance*

**G1. Study of the Second-Order Ferroelectric Transition in Glycine Sulfate.** SOL TRIEBWASSER, *IBM Watson Laboratory.*—Dielectric constant, nonlinearity, and spontaneous polarization measurements have been taken on the recently reported ferroelectric glycine sulfate.[1] This material exhibits the classic second-order type of ferroelectric transition.[2] The properties discussed are described in terms of the usual expansion of the free energy in even powers of the polarization,

$$F = A(T-T_0)P^2 + BP^4 + CP^6, \qquad (1)$$

where $A = 1.96\times10^{-3}$ $(°C)^{-1}$, $T_0 = 49.8°C$, $B = 2.3\times10^{-10}$ $(esu/cm^2)^{-2}$ and $C = 6.3\times10^{-19}$ $(esu/cm^2)^{-4}$. $A$ and $T_0$ are found from measurements of the small signal dielectric constant in the paralectric region above $T_0$. $B$ and $C$ are derived from observations of the spontaneous polarization as a function of temperature below $T_0$. The value of $B$ was measured independently by observations of the dielectric constant of electric field biased crystals[3] above the Curie point. The two results for $B$ agree well within experimental accuracy (10%).

[1] Matthias, Miller, and Remeika, Phys. Rev. **104**, 849 (1956). Single crystals used for this work were kindly furnished by Bell Telephone Laboratories.
[2] See, for example, A. F. Devonshire, Advances in Phys. **3**, 85 (1954).
[3] For details of the method see Drougard, Landauer, and Young, Phys. Rev. **98**, 1010 (1955).

**G2. X-Ray and Neutron Structure Analysis of Ferroelectric Rhombohedral $Pb(Zr_{0.75}, Ti_{0.25})O_3$ at Room Temperature.*** F. UNTERLEITNER, G. SHIRANE,† F. JONA, AND R. PEPINSKY, *The Pennsylvania State University and Brookhaven National Laboratory.*—The solid solution $Pb(Zr_{0.75}, Ti_{0.25})O_3$ is ferroelectric and rhombohedral at room temperature,[1] and is cubic (perovskite) at higher temperature. No ferroelectric rhombohedral structure had been completely established heretofore. A powder x-ray analysis established heavy atom positions in this rhombohedral phase; oxygen positions were determined from a neutron powder pattern. The space group is $R3m$, with cell constants $a = 4.11$ $A$, $\alpha = 89°41'$. Atomic coordinates are: Pb at $(\delta,\delta,\delta)$, with $\delta = 0.575$; (Zr, Ti) at $(\epsilon,\epsilon,\epsilon)$ with $\epsilon = 0.040$; O at $(\gamma,0,0)$, $(0,\gamma,0)$, $(0,0,\gamma)$ with $\gamma = 0.520$. The oxygen octahedra surrounding the (Zr, Ti) atoms are only slightly distorted, and atomic displacements are of the same order as in tetragonal ferroelectric $PbTiO_3$.[2]

* Research supported by Air Force Office of Scientific Research, Signal Corps Engineering Laboratories, and U. S. Atomic Energy Commission.
† On leave of absence from The Pennsylvania State University.
[1] E. Sawaguchi, Jr., Phys. Soc. Japan **8**, 615 (1953).
[2] Shirane, Pepinsky, and Frazer, Acta Cryst. **9**, 131 (1956).

**G3. Neutron Diffraction Study of Magnetic Ordering in $Er_2O_3$.** M. K. WILKINSON, W. C. KOEHLER, E. O. WOLLAN, AND J. W. CABLE, *Oak Ridge National Laboratory.*—Previous neutron scattering investigations[1] of $Er_2O_3$ have shown that at sample temperatures from 295°K to 20°K paramagnetic diffuse scattering exists which arises from a magnetic moment corresponding to that of the free trivalent erbium ion. Neutron diffraction data now obtained at temperatures in the pumped liquid helium range show that antiferromagnetic ordering of the erbium ions occurs at about 4°K. These antiferromagnetic reflections can be indexed on the basis of a magnetic structure in which there are equal numbers of parallel and antiparallel magnetic moments among the nearest neighbors about a given ion and two-thirds of the next-nearest neighbors are antiparallel. If the face-centered cubic lattice of erbium ions is subdivided into four interpenetrating simple cubic lattices, this antiferromagnetic structure is one in which each of the four sublattices has an antiferromagnetic arrangement characteristic of a $C$-type configuration.[2] The temperature dependence of the intensities of the antiferromagnetic reflections and the magnitude of the diffuse scattering suggests that not all the erbium ions are involved in the ordering process.

[1] W. C. Koehler and E. O. Wollan, Phys. Rev. **92**, 1380 (1953).
[2] E. O. Wollan and W. C. Koehler, Phys. Rev. **100**, 545 (1955).

**G4. Neutron Diffraction Study of Magnetic Ordering in $Ho_2O_3$.** W. C. KOEHLER, E. O. WOLLAN, M. K. WILKINSON, AND J. W. CABLE, *Oak Ridge National Laboratory.*—Neutron diffraction studies of $Ho_2O_3$ have been made at temperatures ranging from 4.2°K to 1.25°K and in applied fields extending to 16.3 kilo-oersteds. A complex series of magnetic ordering transitions, apparently field induced has been observed. From 4.2°K to 2.4°K the zero field diffraction patterns exhibit broad diffuse maxima characteristic of short-range antiferromagnetic ordering. At 1.8°K very weak coherent reflections appear which are only slightly more intense at 1.25°K. At 4.2°K, coherent (110), (112), (310), and (312) reflections are observed to grow in almost uniformly with applied field but there still remains a broad maximum centered between the (111) and (200) reflections. Above 1.4°K no reflections of the type (100), (120), etc. are found for any field value; below this temperature reflections of this type occur for fields smaller than 10.0 kilo-oersteds. At 1.25° and at 16.3 kilo-oersteds the observed reflections are of the type (200), (220), etc. and (110), (112), etc. A tentative interpretation of these results relative to the general problem of magnetic ordering on face centered cubic lattices will be described. The loan of the $Ho_2O_3$ by Dr. F. H. Spedding is gratefully acknowledged.

**G5. Temperature Variation of Magnetic Component in Neutron Diffraction of Magnetite.*** L. TENZER† AND T. RISTE,‡ *Brookhaven National Laboratory* (introduced by G. J. Dienes).—The behavior of some reflections of natural magnetite single crystals was studied in the range from room temperature to about 700°C.[1] The single crystal mounted on a goniometer head was enclosed in a quartz tube surrounded by a Nichrome heating wire and the rocking curves, counter fixed, were scanned for each temperature. Each crystal used was first checked for extinction, which was not found severe. Intensities of the (220) and (222) reflections which are respectively produced by ions on tetrahedral and octahedral sites only, were compared with theoretical curves deduced from the Néel's calculations based on the Weiss molecular field.[2] The present data suggest that there is a marked difference and that the experimental curves can be fitted much better with that deduced from a simple Brillouin curve for $S = \frac{1}{2}$. The same conclusion holds for the (111) reflection. A similar study on nickel ferrite and cobalt ferrite is in progress.

* Under the auspices of the U. S. Atomic Energy Commission.
† Belgian American Educational Foundation fellow.
‡ Now at JENER, Kjeller, Norway.
[1] See A. W. McReynolds and T. Riste, Phys. Rev. **95**, 1161 (1954).
[2] L. Néel, Ann. phys. **3**, 137 (1948).

**G6. Theory of the Spontaneous Magnetization of a Ferromagnet near Its Surface.** GEORGE T. RADO, *Naval Research Laboratory.*—It is suggested that each frequency component

of the fluctuating magnetization arising from thermal spin waves possesses a vanishing normal derivative at the surface of a ferromagnetic specimen. Thus each standing spin wave should have an antinode at the surface. On this basis, the fractional deviation of the spontaneous magnetization at temperature $T$ from its value at 0°K is calculated as a function of the distance, $y$, below the surface ($y=0$) of a specimen having a cubic lattice. If $(y+\Lambda)\ll$(specimen dimensions) is assumed, the result becomes

$$\frac{M_0-M_T(y)}{M_0}=\left(\frac{M_0-M_T}{M_0}\right)_{\text{Bloch}}\times\left\{1+[\zeta(\tfrac{3}{2})]^{-1}\sum_{n=1}^{\infty}n^{-\frac{3}{2}}\exp(-y^2/\Lambda^2 n)\right\}.$$

The quantity in braces, being the suggested correction factor to the Bloch $T^{\frac{3}{2}}$ law, is $\{2\}$ at $y=0$ and approximately $\{1+(0.678\Lambda/y)\}$ at $y\gtrsim 2\Lambda$. Here $\zeta(\frac{3}{2})=2.612$ denotes the zeta function of $\frac{3}{2}$, and $\Lambda=(2gA\beta/M_0kT)^{\frac{1}{2}}$ represents a "characteristic length." Additional symbols are: $g$=Landé factor; $A$=exchange stiffness; $\beta$=Bohr magneton; $k$=Boltzmann's constant. Possible extensions and applications of the above result (e.g., to spin wave resonance) are being investigated.

**G7. Modified Ferromagnetic Dynamical Equation.*** HERBERT B. CALLEN, *University of Pennsylvania.*—Conservation of the magnetization in a single domain ferromagnet subject to an applied field requires that

$$d\mathbf{M}/dt=\gamma\mathbf{M}\times\mathbf{H}-\lambda\mathbf{M}\times(\mathbf{M}\times\mathbf{H}),$$

where $\gamma$ and $\lambda$ are arbitrary functions of $\mathbf{H}$. Landau and Lifschitz proposed that, in the absence of further knowledge, $\gamma$ and $\lambda$ tentatively be assumed constant. The resulting dynamical equation is the basis of most current theories of rotational response. A simple spin-wave mechanism of the dissipative process suggests that the field dependence of $\lambda$ is such that

$$d\mathbf{M}/dt=\gamma\mathbf{M}\times\mathbf{H}-\left(\frac{\lambda_0}{MH-\mathbf{M}\cdot\mathbf{H}}\right)\mathbf{M}\times(\mathbf{M}\times\mathbf{H}).$$

This dynamical equation implies that the effective loss, and consequently the ferromagnetic resonant line width, varies inversely as the resonant frequency. Comparison with available experimental data will be exhibited.

* Supported by the Office of Naval Research.

**G8. Shape Dependence of Ferromagnetic Dissipation.*** ERNEST E. PITTELLI AND HERBERT B. CALLEN, *University of Pennsylvania.*—The spin-wave dissipative mechanism referred to in the preceding abstract can couple the zero wave-vector spin wave mode to the lattice indirectly by way of other spin waves, as in the Clogston mechanism, or by other routes. In disordered alloys or ferrites the Clogston mechanism should play a dominant role. The loss parameter $\lambda_0$ then acquires a characteristic dependence on the sample shape. We have evaluated this dependence for a thin-slab geometry, assuming a white spectrum of the perturbative potential. The ferromagnetic resonance line width is predicted to decrease with decreasing thickness of the slab, vanishing for zero thickness. Measurements of Dr. Henry Belson, on thin Permalloy films, will be discussed.

* Supported by the Office of Naval Research.

**G9. Ferromagnetic Resonance of Nearly Perfect Iron Crystals.** D. S. RODBELL, *General Electric Research Laboratory.*—Crystals of iron containing very few imperfections may be grown by the reduction of FeBr.[1] When sufficiently small (ca $10\times10\,\mu\times1$ mm) these whiskers possess mirror-like {100} surfaces and exhibit phenomenal mechanical strength. Ferroresonance absorption—measuring the variation of reflected power of a resonant cavity—yields for one whisker a $\Delta H$ (between maximum variations of reflected power *vs* external magnetic field) of 28±3 oersteds at 315°C and 9 kmcps. This appears to be the narrowest line width yet reported for metallic ferromagnets. The broadening component of this $\Delta H$ due to exchange and conductivity is calculated[2] to be approximately 20 oe. The splitting factor ($g$) is 2.10±0.05 being temperature and frequency independent. The exchange shift which accompanies the broadening is accounted for. At 20 kmcps the limit of error for $g$ is ±0.02 as the anisotropy field is less important compared to the net field. The relation $g-2=2-g'$ appears to be obeyed confirming recent observations.[3]

[1] S. S. Brenner, J. Appl. Phys. **27**, 1484 (1956).
[2] W. S. Ament and G. T. Rado, Phys. Rev. **97**, 1558 (1955).
[3] G. S. Barlow and K. J. Standley, Proc. Phys. Soc. (London) **B69**, 1052 (1956).

**G10. Magnetic Spectra of Manganese Ferrites.** S. R. POLLACK,* S. E. HARRISON, AND C. J. KRIESSMAN, *Remington Rand UNIVAC.*—The magnetic spectra of manganese ferrites of the composition $Mn_{1+x}Fe_{2-x}O_4$ have been measured over the frequency range of one to 1000 Mc ($0\leq x\leq 0.7$). Two resonances are observed in the region above 100 Mc. The lower frequency peak (peak $A$) demonstrates a maximum in $\mu''$ between 150–190 Mc as the manganese content is varied while the higher peak ($B$) varies between 370 and 570 Mc. As the value of $x$ increases, the resonance frequency ($\nu_r$) decreases. Peak ($B$) can be associated with a natural spin resonance in the anisotropy field according to the Snoek formula.[1]

$$\nu_r=\frac{2}{3\pi}\gamma\frac{K}{M_s}.$$

If we know the magnetization ($M_s$), we can obtain the dependence of the anisotropy ($K$) on $x$. A theory based on the ionic distribution of the cations $Mn^{2+}$ and $Mn^{3+}$ will be presented to explain both the calculated values of anisotropy and the measured values of the magnetic moment. Peak $A$ may be attributed to a domain wall resonance.[2] Measurements on powdered samples and on solid samples in the remanent state will be shown to support these hypotheses.

* Permanent address: University of Pennsylvania.
[1] J. L. Snoek, Physica **14**, 207 (1948).
[2] G. T. Rado, Phys. Rev. **80**, 273 (1950).

**G11. Antiferromagnetic Resonance Using Pulsed Magnetic Fields and Millimeter Wavelength Radiation.*** SIMON FONER, *Lincoln Laboratory.*—Applicability of oscillatory pulsed field techniques described earlier[1] (capable of producing over 750 kilogauss) and millimeter waves to investigations of resonance in antiferromagnetic materials is discussed. When the applied frequency is much less than the zero field splitting, the high field antiferromagnetic resonance mode can be observed with applied fields close to the critical field. Such high field resonance has been observed in single crystal $MnF_2$[2] at 4.2°K using 70 kmc/sec with the applied field along the $c$ axis, indicating a critical field at 4.2°K of 95 kilogauss ±5%. These results are in good agreement with theoretical estimates of Keffer[3] and extrapolations of Johnson and Nethercot's[3] recent data obtained at higher temperatures. Experiments in progress on $MnF_2$ as a function of temperature and orientation will also be presented along with a brief survey of similar experiments on single crystal $Cr_2O_3$[4] and $FeF_2$,[2] polycrystalline zinc ferrite and related materials.

* The research reported in this document was supported jointly by the U. S. Army, Navy, and Air Force, under contract with M.I.T.
[1] S. Foner and H. H. Kolm, Rev. Sci. Instr. **27**, 547 (1956); Bull. Am. Phys. Soc. Ser. II, **1**, 298 (1956); Conference on Magnetism and Magnetic Materials, Boston (October, 1956).
[2] Kindly provided by Professor J. W. Stout of the University of Chicago.
[3] F. Keffer, Phys. Rev. **87**, 608 (1952); F. M. Johnson and A. H. Nethercot, Jr., Phys. Rev. **104**, 847 (1956).
[4] Kindly provided by Dr. T. R. McGuire of the U. S. Naval Ordnance Laboratory.

**G12. Ferrimagnetic Resonance in Yttrium Iron Garnet (YIG) Samples of Various Shapes.** J. F. DILLON, JR., *Bell*

*Telephone Laboratories.*—Recently, ferrimagnetic resonance work has been reported on single crystals of yttrium iron garnet (YIG).[1] The narrow lines as well as some of the other striking features made it seem important to observe the resonance in specimens of various shapes. Thin circular disks of various sizes, orientations, and aspect ratios (0.06 is typical) were cut from single crystals.[2] These have been examined at several frequencies and temperatures and in a variety of microwave and steady field configurations. The magnetostatic mode structure[3] previously reported for such experiments with manganese ferrite crystals was observed for the YIG samples. However, the line width of the spatially uniform mode of precession shows more shape dependence than in the manganese ferrite case. As an example, line widths of only a few oersteds have been observed in disks of material which as sphere show line widths of about 25 oe. The relation of these results to the recent theoretical proposals of Clogston *et al.*[4] will be discussed.

[1] J. F. Dillon, Bull. Am. Phys. Soc. Ser. II, **2**, 22 (1957); Phys. Rev. **105**, 639 (1957).
[2] Grown by J. W. Nielsen.
[3] J. F. Dillon, Bull. Am. Phys. Soc. Ser. II, **3**, 125 (1956); L. R. Walker, Bull. Am. Phys. Soc. Ser. II, **3**, 125 (1956) and Phys. Rev. **105**, 390 (1957).
[4] Clogston, Suhl, Walker, and Anderson, Phys. and Chem. Solids (to be published).

**G13. Effective Gyromagnetic Ratios for Triangular Ferrimagnetic States.** A. ESKOWITZ* AND R. K. WANGSNESS, *U. S. Naval Ordnance Laboratory and University of Maryland.*—Yafet and Kittel have predicted the existence of angles between the $B$-sublattice magnetizations as a possible state of a ferrimagnetic at absolute zero. Lotgering has found such states necessary to explain fully his magnetization values for certain chromium spinels. Using the molecular field approximation and the semiclassical equations of motion for each sublattice magnetization, we have found that the triangular state can also be described by an effective gyromagnetic ratio. This effective ratio depends explicitly on the ratio of the $B-B$ interaction to the $A-B$ interaction rather than on the static components of the $A$- and $B$-sublattice magnetizations as for the antiparallel state. The effective gyromagnetic ratio for the triangular state will differ the most from that for the antiparallel state when the ratio of the interactions ($B-B$ to $A-B$) is greatly different from the $A$- to $B$-magnetization ratio and/or the gyromagnetic ratios of the $A$- and $B$-sublattices are much different. We also find that the shift in the values of the gyromagnetic ratios for $FeCr_2O_4$ and $NiCr_2O_4$ should be experimentally observable if these spinels have a transition from a triangular to an antiparallel state.

* Now with Sperry Rand Corporation.

**G14. Magnetic Resonance Saturation in Lithium at Intermediate Values of $H_1$.*** D. F. HOLCOMB, *Cornell University.*—The saturation behavior of the nuclear resonance in lithium metal has been studied at room temperature and at 77°K by observing the shape and amplitude of the absorption signal as a function of rf field $H_1$. At 77°K, the change in shape of the absorption upon saturation noted previously[1,2] in other solids is observed. A tendency toward a Lorentzian shape from the unsaturated Gaussian shape is evident at values of $H_1 \geqq 1.6 \times 10^{-2}$ gauss. (The unsaturated line width at half-maximum is $6.5 \pm 0.3$ gauss.) At room temperature, previous measurements have indicated that the lithium spin system follows the Bloch equations, with $T_1 \neq T_2$. However, it is found that the line does not saturate according to the Bloch equations. Measurements of the shape and width of the line will be presented and discussed. The Bloch equations must be modified along the line suggested by Redfield[3] for the case of very large $H_1$. Measurements of width and amplitude of the proton resonance absorption in $FeCl_3$-doped $H_2O$ as a function of $H_1$ have been made and show that in this system, with $T_1 = T_2$, the Bloch equations correctly describe the saturation behavior.

* Work supported in part by the Office of Naval Research.
[1] D. F. Abell and W. D. Knight, Phys. Rev. **93**, 940 (1954).
[2] A. G. Redfield, Phys. Rev. **98**, 1787 (1955).

**G15. $F^{19}$ Nuclear Magnetic Resonance Line Shapes in $CaF_2$.** C. R. BRUCE, *Washington University.*—The theory proposed by Van Vleck[1] for the nuclear magnetic resonance dipolar line shapes in a crystalline solid was to a large extent confirmed by the measurements of Pake and Purcell.[2] These measurements have been repeated using the same crystal that was used by the early investigators but using a spectrometer of improved design. The new data are in better agreement with theory in the case of the magnetic field along a [111] crystal direction and remain in good agreement for the [110] and [100] crystal directions. A polar plot of line width *versus* crystal orientation shows the line shape is a very sensitive function of magnetic field direction about the [111] crystal direction. The comparison with theory was extended to the fourth moments of the line shapes for the new data without appreciably increasing the error arising from a loss of the signal at the tails of the resonance in the noise. The fourth moments are in good agreement with values calculated from the theory of Van Vleck using the 26 nearest neighbors.

* Supported in part by the Office of Naval Research and Office of Scientific Research.
[1] J. H. Van Vleck, Phys. Rev. **74**, 1168 (1948).
[2] G. E. Pake and E. M. Purcell, Phys. Rev. **74**, 1184 (1948).

## THURSDAY AFTERNOON AT 2:00

## Houston Hall Auditorium

## (P. H. MILLER presiding)

### *Semiconductor Surface Phenomena; Whiskers*

**H1. Low-Temperature Behavior of Germanium Single Crystal Layers.*** CLAUD M. KELLETT, H. FRITZSCHE, AND K. LARK-HOROVITZ, *Purdue University.*—Single crystal layers of germanium down to 12 microns have been prepared using grinding and etching techniques. A method is described for grinding the layers that provides a constant check of layer thickness during the course of grinding. Electrical measurements have been performed to determine whether thin layers behave like bulk material in the temperature range of liquid helium where impurity band conduction is important. The curves of resistivity and Hall coefficient as functions of reciprocal temperature indicate that thin layers of $N$ type and $P$-type germanium behave like the bulk material in the temperature range between 1.3°K and 300°K if the layers are free from strain. In order to avoid strains it has been found necessary to use a high resistivity germanium substrate and a very thin layer of bonding material. Measurements of thin layers on glass substrates show gross deviations from bulk behavior,† the result of strains in the layer produced by the different thermal expansion coefficients of glass and germanium. Thick layers of bonding materials produce deviations similar to those observed for the glass substrate.

* Work supported by a U. S. Signal Corps contract.
† In the temperature range of impurity band conduction.

**H2. Low-Temperature Trapping on Germanium and Silicon Surfaces.** S. ROY MORRISON, *Honeywell Research Center.*—Field effect measurements on germanium and silicon at liquid nitrogen temperature yield nonexponential and asymmetric decay curves which can be interpreted as representing the trapping of carriers in surface recombination levels. Only if the disturbance (applied field) is low do the decay curves approach an exponential and symmetric form. With larger disturbances, when the field is of a sign to trap minority carriers the decay is abnormally slow exhibiting time constants equal to and larger than the low disturbance time constant. With a field to trap majority carriers, the time constants are equal to and smaller than the low disturbance value. As with bulk slow recombination, here also the decay is sensitive to temperature and illumination, apparently corresponding to changes in minority carrier density. Above 175°K, the decay rate with *n*-germanium (used for most of the measurements) is too rapid to be followed on a recorder. Below about 160°K in the dark, it is too slow. However, it can be arbitrarily accelerated by illumination or minority carrier injection. Agreement is found between the results on *n*-germanium and a model which assumes the surface barrier to be one of the dominant parameters. Assuming the model correct, the bulk minority carrier density can be directly measured using the effect.

**H3. Variation of Surface Recombination Velocity with Surface Potential on Silicon.** B. BERNSTEIN AND C. S. MCCARTHY, JR., *Philco Corporation.*—The variation of the surface recombination velocity with surface potential on thin single-crystal silicon wafers has been studied. The surface potential was varied by cycling wet and dry nitrogen and oxygen ambients over the samples. The changes of surface potential were determined by monitoring the wafer conductance and applying curves of surface conductance *vs* surface potential. The surface recombination velocity was measured by observing a photoconductive decay.[1] The results for 17 ohm cm and 25 ohm cm *p*-type and for 13 ohm cm and 17 ohm cm *n*-type silicon show in most cases nearly constant surface recombination velocity, $S$, over a 0.4- to 0.5-volt range of surface potential. The values of $S$ vary with the different samples and can change considerably on a given sample after a re-etch. If $S$ is on a plateau symmetric about intrinsic surface potential,[2] the results are consistent with a trapping center lying within 0.15 ev of the band edge. A corroborative experiment on the variation of $S$ with temperature yields an activation energy of 0.076 ev.

[1] D. T. Stevenson and R. J. Keyes, J. Appl. Phys. **26**, 190 (1955).
[2] D. T. Stevenson and R. J. Keyes, Physica **20**, 1041 (1954).

**H4. Energy Level Structure of Surface States and Values of the Surface Potential in Germanium and Silicon.** GEORGE C. DOUSMANIS, *RCA Laboratories.*—Recent experiments on field-induced effects on the surface recombination ($s$) of Ge and Si yield direct evidence of discrete energy level structure of the recombination states. Theoretical expressions are derived which relate $s$ to the surface potential $\phi_s$ and the properties of the surface states. Application to experiment yields the following information:

| Material | Structure | Energy (ev) from middle of forbidden band | Capture cross-section ratio $\sigma_p/\sigma_n$ |
|---|---|---|---|
| *n*-type Ge 0.3 to 3 ohm-cm | Single level | $0.34\pm0.02$ or $-0.34\pm0.02$ | ~1 |
| *n*-type Ge 12 to 15 ohm-cm | Two levels: Level 1 | $0.30\pm0.03$ | $\sim3\times10^{-4}$ |
| | Level 2 (twice as effective for recombination) | $-0.30\pm0.03$ | $\sim3\times10^{4}$ |
| *p*-type Si 0.1 ohm-cm | Single level | $0.47\pm0.03$ or $-0.47\pm0.03$ | |

$\phi_s$ is determined from the maximum of $s$. In Ge $\phi_s$ can change from 0.35 v to −0.35 over the Bardeen-Brattain cycle of ambients. In Si values up to 0.5 v are observed. This technique can also be used in determining the time constants and other properties of the slow states.

**H5. Surface Photovoltage Decay Method for Measuring Carrier Lifetimes in Semiconductors.** E. O. JOHNSON, *RCA Laboratories* (introduced by G. C. Dousmanis).—The decay of the surface photovoltage[1] affords a new means for measuring minority carrier lifetimes in semiconductors. This has the outstanding advantage that no physical contacts on the specimen are required. The experimental arrangement consists of a pulsed light source, an oscilloscope with a low gain preamplifier, and a semiconductor specimen making capacitive contact with two electrodes. Electrode $A$ is semitransparent and detects the surface photovoltage $\Delta Y$ generated under it by a light pulse. Electrode $B$, the circuit return, is located anywhere on the side or back of the specimen over a region where there is no increase $\Delta_m$ in the minority carrier density. If the injected carrier density near $A$ is made low so that $\Delta Y = 1$ mv, or less, then $\Delta Y$ is a linear function of $\Delta_m$ and can be used to measure the lifetime of $\Delta_m$. The results obtained by this new technique will be compared with those obtained from the conventional photoconductivity decay method.

[1] E. O. Johnson, Bull. Am. Phys. Soc. Ser. II, **2**, 66 (1957).

**H6. Field-Effect under Illumination.** G. WALLIS AND S. WANG, *Sylvania Electric Products, Incorporated.*—In the conventional investigation of recombination traps on semiconductor surfaces, measurement of surface recombination velocity $v_s$ as a function of barrier height gives information about the energy levels and capture probabilities of the traps. The method breaks down if the density or position of the traps changes during the measurements. A method will be described which is less sensitive to these changes. A small signal ac field is applied to a steadily illuminated filament surface (field-effect under illumination). The resulting changes in filament conductance consist of changes in surface conductance (dark field-effect) and photoconductance, $\Delta G_L$, the latter resulting from the field-induced changes in $v_s$. A plot of $\Delta G_L/G_L$ *versus* barrier height gives information about trap levels and capture probabilities. In the presence of a single dominant trap, $\Delta G_L/G_L$ is independent of trap density, provided surface recombination predominates over bulk recombination. In a complicated case, the $\Delta G_L/G_L$ plot can differentiate between various possible interpretations of a $v_s$ plot, e.g. an interpretation based on a single trap with trap density or energy assumed to be a function of barrier height or an interpretation which takes these quantities to be constants but assumes two sets of traps.

**H7. Investigation of Recombination Process on Germanium Surfaces.** S. WANG AND G. WALLIS, *Sylvania Electric Products, Incorporated.*—Surface recombination velocity, field-effect under illumination, and the dark field-effect were measured as a function of barrier height on germanium slabs exposed to the Brattain-Bardeen ambient cycle. The barrier height was obtained by measuring the sample dc conductance. Results on a 35 ohm-cm, *n*-type and on a 23 ohm-cm, *p*-type sample will be discussed. Over a range of barrier height $\pm0.1$ ev on either side of the intrinsic surface, the surface recombination process was predominantly controlled by traps having a ratio of hole to electron capture probability of 9 and energy levels $E_t - E_i = 0.097$ and $-0.041$ ev. These trap energies also fit the dark field-effect data. A case will be presented where the trap density was changing during the ambient cycle and another where, as the surface became very *n*-type, the effect of another recombination trap began to show up. In both cases a unique interpretation of the results was possible only when the field-effect under illumination and the surface re-

combination velocity were analyzed side by side. With regard to the first case, a similar change in trap density was also observed in the dark field-effect. Therefore, it seems that the same traps are operative in the surface recombination process and in the dark field-effect.

**H8. Fast Field Effect and Photoconductive Studies on Lead Sulfide Films.** HOWARD E. SORROWS, *Office of Naval Research and U. S. Naval Ordnance Laboratory.*—Estimates by Petritz[1] indicate that surface trap densities, rather than bulk trap densities, should give observed photoconductive time constants on lead sulfide films. The field effect measurement can be used to study surface traps. We reported[2] a fast field effect time constant, $\tau_f \cong 250$ μsec, measured by the transient response method. We have since developed a double ac method which eliminates some of the balancing difficulties of the transient or single ac methods on high impedance samples. The sample is placed in an ac bridge; another ac field of different frequency is applied normal to the film surface. The field effect voltage is the unbalanced bridge voltage at the sum and difference frequencies. $\tau_f$ determined from the conductance *vs* frequency curve was found to be in good agreement with $\tau_p$, the photoconductive time constant. Background illumination was used to vary (shorten) the time constants; $\tau_f$ and $\tau_p$ decrease and remain equal within experimental error. These results indicate that the trapping centers of photoconductivity are probably surface states and adds further verification to the majority carrier model of photoconductivity.[2]

[1] Richard L. Petritz, Bull. Am. Phys. Soc. Ser. II, 1, 177 (1956).
[2] Petritz, Lummis, Sorrows, and Woods in *Semiconductor Surface Physics*, edited by R. H. Kingston (University of Pennsylvania Press, Philadelphia, to be published).

**H9. Magnetosurface Effects.** JAY N. ZEMEL AND RICHARD L. PETRITZ, *U. S. Naval Ordnance Laboratory.*—The conduction of charge in the space charge region near the surface of a semiconductor is characterized by a charge density and mobility which is usually different from the bulk values. Schrieffer[1] has presented a theory which leads to a reduced mobility for the current carriers in the space charge region. To date, there has been no direct demonstration of this reduction in mobility. We have constructed an apparatus capable of measuring small changes in the Hall and magnetoresistive effects. Data has been taken on high-resistivity germanium while varying the ambient gas. Large changes in conductivity, Hall constant, and magnetoresistive effect have been observed. The Hall mobility and magnetoresistive effect both decrease as qualitatively predicted by theory.

[1] J. R. Schrieffer, Phys. Rev. **97**, 641 (1955).

**H10. Growth of Whiskers from the Vapor.*** R. V. COLEMAN AND N. CABRERA, *University of Virginia.*—Following the experiments of W. G. Sears and R. V. Coleman,[1] whiskers of Zn have been grown from its own vapor in the presence of an inert gas: He, A, Kv, etc. Emphasis was given to the concentration of impurities in the gas, particularly oxygen. For specific condition of supersaturation and temperature, and to some extent independent of the impurity content, long whiskers grow. For some of them and at particular position along the whiskers, perfect hexagonal plates grow sidewise, parallel to each other, giving indication of the crystallographic orientation of the whiskers. The whisker is never normal to the plates and no indication of twisting has been observed.

* Work supported partially by the National Science Foundation and the Office of Naval Research.
[1] G. W. Sears and R. V. Coleman, J. Chem. Phys. **25**, 635 (1956).

**H11. Production and Properties of Graphite Whiskers.** R. BACON AND J. C. BOWMAN, *National Carbon Company.*—Graphite whiskers have been produced under various conditions in a consumable electrode arc. The whiskers are found embedded in the solid boule which is built up by deposition from the electrode. These whiskers exhibit qualitatively many of the properties observed in metal whiskers. Their diameters range from a few tenths to over ten microns, with lengths up to 1.6 cm. Their tensile strengths are at least 20 000 pounds per square inch and the electrical conductivity is nearly as high as that of single crystal graphite. The bending strain required to kink a whisker expressed as the ratio of whisker radius to radius of curvature just before kinking is approximately 0.1%. Electron micrographs usually show a uniformly dense cylinder having straight sides, with occasional step changes in diameter. Electron and x-ray diffraction shows that the *c* axis is perpendicular to the whisker at all azimuths, and the cylinder axis is the hexagonal *a* axis. The whiskers are quite crystalline and it is likely that the structure consists of wrapped-up cylindrical sheets of graphite layer planes.

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THURSDAY AFTERNOON AT 2:00

Physical Sciences, Room A-2

(J. W. BEAMS presiding)

## *General Physics*

**HA1. A Variational Method for Nonlinear Microwave Cavities.** HARVEY SCHULTZ AND P. H. MILLER, JR., *General Atomic.*—The properties of a microwave cavity filled with a nonlinear dielectric have been investigated by a variational method based on Hamilton's principle. The Lagrangian density which leads to the proper wave equation is not the difference between the electrostatic and magnetic energy densities but rather

$$L_4 = \int_0^E D \cdot dE - \frac{\mu H^2}{2}.$$

Using trial solutions in the method described by Miller[1] it is found that rectangular cavity can be made to oscillate simultaneously at both the fundamental and the third harmonic frequencies for finite driving fields. It does not appear that this is a suitable method for generating harmonics. For example, if the amplitude of the fundamental is large enough to change the dielectric constant at the peak by 20% the fraction of the cavity energy associated with the third harmonic is $10^{-4}$.

[1] P. H. Miller, Jr., Am. J. Phys. **25**, 30 (1957).

**HA2. Use of Complex Conductivity in the Representation of Dielectric Phenomena.** F. A. GRANT, *National Bureau of Standards.*—It is customary to express the dielectric properties of materials in terms of the real ($\epsilon'/\epsilon_0$) and imaginary ($\epsilon''/\epsilon_0$) components of the complex dielectric constant. In the Cole-Cole diagram, the experimentally determined values of $\epsilon'$ and $\epsilon''$ corresponding to various frequencies are plotted in

Cartesian coordinates. When the mechanism is a simple Debye relaxation, this diagram takes the form of a semicircle having its center on the $\epsilon'$ axis. When $\sigma_0$, the dc conductivity of the material, is not negligible, the low-frequency part of the Cole-Cole plot loses its distinctive shape. A complementary representation in terms of complex conductivity will be proposed, in which a simple Debye mechanism again results in a semicircle. However, a nonzero value of $\sigma_0$ does not cause this representation to lose its distinctive shape in the low frequency range. Instead, the effect of $\sigma_0$ is merely to cause a shift in the position of the center of the semicircle, which enables $\sigma_0$ to be obtained directly from the diagram. Examples of the utility of this representation will be given.

**HA3. Relation between Complex Conductivity and Complex Permittivity.*** P. H. FANG, *National Bureau of Standards.*—When the dielectric dispersion is of the Debye type, with a single relaxation time, Grant (preceeding abstract) has shown that a plot of complex conductivity is complementary to the Cole-Cole plot of complex permittivity.[1] Three points will be discussed: 1. Another plot is introduced based on the case when the dispersion is of Debye type, there is a linear relation between the conductance $\sigma'$ ($=\omega\epsilon''$, with $\omega$ the frequency, $\epsilon''$ the dielectric absorption) and the dielectric constant $\epsilon'$. The slope of $\epsilon'-\sigma'$ line then gives the relaxation time $\tau$. This presentation of experimental data gives a precise value $\tau$ in a more convenient way than the semicircular fitting. 2. Comparison will be made among the representations of Cole-Cole, Grant, and $\epsilon'-\sigma'$, for the case of general Cole-Cole distribution,[1] which introduces a distribution parameter $\alpha$ (the depression of the semicircle center below $\epsilon'$ axis). 3. A Kramers-Kronig type of relation for the complex conductivity will be discussed. This relation can be used to determine $\sigma'$ from the frequency spectrum of $\sigma''(=\omega\epsilon')$, or vice versa.

* Research supported by the U. S. Atomic Energy Commission.
[1] K. S. Cole and R. H. Cole, J. Chem. Phys. **9**, 341 (1941).

**HA4. Low-Pressure Corrections for Recombination Measurements in Nitrogen.** A. C. FAIRE AND K. S. W. CHAMPION,* *Air Research and Development Command.*—Recombination measurements have been previously made in $N_2$ and $N_2-He$ mixtures using microwave techniques.[1-3] The He was added to reduce diffusion losses when the $N_2$ pressure was low, and it was assumed that it would act simply as a passive recoil agent. The limitations of He as a passive recoil gas have been studied analytically and also experimentally by means of a monochromator and a photomultiplier. Accurate values of the rate coefficient for dissociative recombination in $N_2$ at low pressures[4] have been obtained after corrections were made for diffusion loss and for ionization produced in the afterglow by He metastables.

* Tufts University.
[1] Faire, Fundingsland, and Aden, Gaseous Electronics Conference, October, 1953, Washington, D. C.
[2] Faire, Fundingsland, and Aden, Conference on Electron Physics, June, 1954, University of Birmingham, Birmingham, England.
[3] A. C. Faire and George W. Griffing, Gaseous Electronics Conference, October, 1955, Schenectady, New York.

**HA5. Separation of the $\alpha_1-\alpha_2$ Doublet of X-Ray Diffraction Lines.** A. D. FRANKLIN AND B. F. CANTY, *National Bureau of Standards.*—If the Fourier coefficient of a doublet be calculated from the data, then it is possible in a simple fashion to calculate the coefficients of the single-component line. This calculation requires that, as in the $\alpha_1-\alpha_2$ case, the separation of the components be known. This technique will be demonstrated using data taken with a well-crystallized $BaTiO_3$ ceramic specimen. The extension of this technique to the resolution of a doublet in which the separation of the components is not known will be discussed.

**HA6. Hartree-Fock Wave Functions for $(3d)^{10}$ Atomic Configurations in the First Long Series.** WILLIAM W. PIPER, *General Electric Research Laboratory.*—Wave functions have been obtained for the isoelectronic series from $Cu^+$ to $Kr^{+8}$. These calculations were performed with the aid of an IBM 650 computer. Details of this program have been described elsewhere.[1] Hartree's interpolation techniques[2] were used to obtain starting functions and were found for this closed shell series to be quite accurate. Hartree predicts the screening constant, $\sigma$, should be linear in $\bar{r}$, and for the $3d$ shell, for example, one obtains from $Cu^+$ and $Ge^{+4}$ the expression $\sigma=14.298+4.052\bar{r}$. The greatest deviation from this formula was $\Delta\sigma=0.02$ for $Kr^{+8}$ which corresponded to a maximum error of 0.02 in the wave function. The corresponding maximum error in the amount of charge within an arbitrary radius due to all the $3d$ electrons was 0.08 of an electronic charge. Slater's table of energy levels[3] proved quite useful for starting estimates of all eigenvalues. The final eigenvalues for the $3d$ shell from $Cu^+$ to $Kr^{+8}$ were found to be 1.62, 3.07, 4.82, 6.84, 9.11, 11.64, 14.42, and 17.42 rydbergs.

[1] W. W. Piper, Commun. and Electronics (Am. Inst. Elec. Engrs.) 1956–1957, p. 152.
[2] D. R. Hartree, Proc. Cambridge Phil. Soc. **51**, 684 (1955).
[3] J. C. Slater, Phys. Rev. **98**, 1039 (1955).

**HA7. Orbit-Orbit Interactions in Atomic Spectra.** C. W. UFFORD AND H. B. CALLEN,* *University of Pennsylvania.*—Empirical spectroscopic evidence suggests the existence of an orbit-orbit interaction between electrons, of the form $\alpha\mathbf{l}_1-\mathbf{l}_2$, and of a magnitude comparable to the spin-orbit interaction. The direct magnetic interaction, present in the Breit equation, if of this form. However, approximate evaluations of the magnetic interaction have given discouragingly small values, and it has been generally believed that the empirical $\alpha\mathbf{l}_1-\mathbf{l}_2$ interaction results from configuration interaction rather than from a magnetic interaction. We have carried out an explicit calculation of the magnetic interaction, using the tensor operator form of the magnetic interaction, as given by Yanagawa. The result of this simple calculation is that the magnetic interaction does indeed give an orbit-orbit interaction comparable in magnitude to the spin-orbit interaction. The retardation effects in the magnetic interaction are found to be the dominant source of the interaction. Previous estimates were based on the unretarded magnetic interaction. The qualitative semiclassical resason for the small contribution of the unretarded magnetic interaction will be discussed. The role of electron correlation in the magnetic interaction has certain unique features as compared with spin-spin and spin-orbit interactions, and these also will be discussed.

* Supported by Office of Naval Research.

**HA8. Inelastic Molecular Collisions with a Maxwellian Interaction Energy.*** B. WIDOM, *Cornell University.*—The radial Schrödinger equation for arbitrary values of the angular momentum is solved exactly with a repulsive $R^{-4}$ potential energy, the solutions being nonperiodic Mathieu functions whose arguments are linear functions of $\log R$. It is shown how to normalize the functions to unit amplitude of oscillation at $R=\infty$, and the results are then used to study vibrational relaxation in the distorted wave approximation. Emphasis is on temperatures sufficiently low, or vibrations sufficiently stiff, so that $h\nu\gg kT$, where $h\nu$ is the energy which is exchanged between vibration and translation. The energy exchange probability per collision, $p$, is found to be proportional to a sinusoidal factor which may have a value anywhere between 0 and 1, depending on the precise magnitude of $h\nu$; and proportional to a factor which decreases as the exponential of $(h\nu)^{\frac{1}{2}}$. Near the threshold $p$ satisfies the threshold theorem,[1] and also decreases extremely rapidly with increasing angular momentum. The energy dependence far from the threshold is also obtained,

and the relaxation time and its temperature dependence are discussed.

* Work supported by U. S. Air Force Office of Scientific Research.
[1] B. Widom, J. Chem. Phys. **23**, 2377 (1955).

**HA9. New Approach to the Study of Electronic Structure of Molecules: Application to $Li_2$.*** T. Arai, *Kyoto University and Carnegie Institute of Technology.*—To remedy deficiencies of orbital approaches, Moffitt[1] proposed incorporation of exact atomic energies into molecular calculations. Rough calculations using equal effective charges for neutral atom and ion give disappointing results, however. Unmodified atomic eigenfunctions also are not suitable because effective charges in molecules may be different from those in free atoms. We start by constructing the primitive Hartree-like function $\psi$ for each atomic eigenfunction. By multiplying $\psi$ by a suitable correction factor $\rho$ we then change effective charges to give equal effective charges for atoms and ions. The modified functions $\chi = A\psi\rho$ finally obtained still contain correlation. In molecular calculations exact eigenvalues of atoms thus are used, but energy changes resulting from deformations of atoms and interatomic interactions are calculated using approximate functions $\chi$ made up from compromise orbitals with a single effective charge. Energy levels of $Li_2$ have been calculated, giving a dissociation energy of 0.95 ev (obs. 1.03 ev).

* Supported in part by the Office of Ordnance Research, U. S. Army.
[1] W. Moffitt, Proc. Roy. Soc. (London) **A210**, 245 (1951).

**HA10. Moments of the Charge Distribution of Molecules.*** Martin Karplus, Aron Kuppermann, and Leonard Isaacson, *University of Illinois.*—For the calculation of the moments of the charge distribution of a molecule whose wave function is expressed as a linear combination of determinants of Slater functions, a large number of one electron moment integrals is required. A general formula for the evaluation of these integrals has been developed and coded for the electronic digital computer at the University of Illinois (ILLIAC). The use of the codes in testing certain approximate charge distributions and indetermining wave function parameters from microwave line broadening and other experimental data will be illustrated by a discussion of some hydrocarbon and other polyatomic molecules.

* Work supported in part by a grant from the University of Illinois Graduate Research Board.

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Thursday Afternoon at 6:00

Indian Arts Gallery, University Museum

(G. Zener presiding)

***Business Meeting of the Division of Solid-State Physics***

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Friday Morning at 9:30

Museum Auditorium

(H. D. Smyth presiding)

***DSSP Symposium on Nuclear Magnetic Resonance***

**J1. Nuclear Spin Behavior in Solids in Strong Radio-Frequency Fields.** A. G. Redfield, *IBM Watson Laboratory.* (25 min.)

**J2. Nuclear Resonance in Solids under High Hydrostatic Pressure.** G. B. Benedek, *Harvard University.* (25 min.)

**J3. Nuclear Magnetic Resonance in the Iron-Group Fluorides.** R. G. Shulman, *Bell Telephone Laboratories.* (25 min.)

**J4. Study of Superconductors by Nuclear Magnetic Resonance.** F. Reif, *University of Chicago.* (25 min.)

**J5. Free Induction Decays in Solids.** I. Lowe, *Washington University.* (25 min.)

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Friday Morning at 9:30

Irvine Auditorium

(M. Lax presiding)

***Elemental Semiconductors***

**K1. Valence Band Structure of Silicon.** Homer D. Hagstrum, *Bell Telephone Laboratories.*—Herman[1] finds that two valence electrons in silicon are in bands ($V3$ and $V4$) whose total width is about 15 ev, and two are in bands ($V1$ and $V2$) at the top of the $V3$ band which are considerably narrower (perhaps 10% of $V3+V4$). Evidence confirming this general band structure has been obtained in studies of the surface Auger effect for silicon. Here, one measures the energy distribution of electrons ejected by the Auger neutralization of 10 ev $He^+$ ions.[2] Two quantitative conclusions are: 1. The top of the valence band in silicon lies about 6 ev below the vacuum level for an essentially atomically clean surface. 2. The width

of the $V1$ and $V2$ bands is about 5 ev. This width is greater than the theoretical. However, Herman,[1] whose latest value is about 1 ev, points out that inculsion of more terms would increase the calculated width. The earliest calculations gave zero width for the $V1$ and $V2$ bands.[2]

[1] F. Herman (private communication) and Proc. Inst. Radio Engrs. **43**, 1703 (1955).
[2] H. D. Hagstrum, Phys. Rev. **96**, 326, 336 (1954); **104**, 672 (1956).
[3] G. E. Kimball, J. Chem. Phys. **3**, 560 (1935).

**K2. Magnetic Susceptibility of Silicon.** D. K. Stevens, W. J. Sturm, E. Sonder, J. W. Cleland, and J. H. Crawford, Jr., *Oak Ridge National Laboratory.*—In addition to the data previously reported,[1] measurements have been carried out on $n$ and $p$ type silicon single crystals with carrier concentrations above $10^{18}$ cm$^{-3}$ in the exhaustion range. The influence of the freezing out of carriers is clearly visible in the curves for three $n$ type samples. The value of $\langle f_s^2 \rangle$, the square of the reciprocal mass tensor appropriately averaged for motion of the electrons in the magnetic field, calculated from these measurements is appreciably less (approximately $\frac{1}{3}$) than that expected from cyclotron resonance measurements.[2] Fast neutron bombardment of intrinsic silicon results in a slight increase in its diamagnetic susceptibility. In extrinsic $p$ type materials the contribution of the holes to the total susceptibility which is paramagnetic prior to irradiation is destroyed when the holes are trapped in irradiation introduced traps. The effect of bombardment upon the susceptibility of $n$ type silicon is inconclusive.

[1] D. K. Stevens and J. H. Crawford, Jr., Bull. Am. Phys. Soc. Ser. II, **1**, 117 (1956).
[2] Dexter, Lax, Kip, and Dresselhaus, Phys. Rev. **96**, 222 (1954).

**K3. Pressure Induced Changes in the Optical Absorption of Ge, Si, Te.*** L. J. Neuringer,† *University of Pennsylvania.*—Measurements of the intrinsic optical absorption coefficient have been made on thin single crystal specimens in the pressure range 1–1000 atmos. The most recent version of the Bardeen, Blatt, Hall theory has been used to determine the pressure coefficient of the (111) conduction band minimum in germanium by extrapolation to zero absorption coefficient. This value is $8.1\times10^{-6}$ ev/atmos with the value for the (000) minimum being about 50% larger. The discrepancy between optical and electrical values of the pressure coefficient may be explained by assuming a pressure dependence of the temperature coefficient of the energy gap. In silicon the pressure coefficient is $-1.8\times10^{-6}$ ev/atmos, in agreement with Warschauer, Paul, and Brooks. Both $Eg_{\perp}$ and $Eg_{\parallel}$ in tellurium decrease with increasing pressure. There is an indication that initially $Eg_{\perp}$ decreases more rapidly with pressure than $Eg_{\parallel}$, in accord with the calculations of Reitz. These pressure coefficients then permit a direct calculation of the lattice dilatation effect of temperature.

* Work supported by a U. S. Navy contract.
† Now at Raytheon Manufacturing Company.

**K4. Conductivity Mobilities in Heavily Doped Silicon.** G. Backenstoss, *Bell Telephone Laboratories.*—Mobilities have been determined in a region in which ionized impurity scattering is predominant. Resistivities were measured by a four point probe and impurity concentrations were obtained from a thermal neutron activation analysis. Measurements were taken with several group III and group V impurities up to concentrations of $6\times10^{19}$ (cm$^{-3}$) and $6\times10^{18}$ (cm$^{-3}$) for $n$ and $p$ type silicon respectively. An effective mobility $\mu'$ can be defined by the equation $\mu' = 1/\rho e N'$ relating $\mu'$ with the total impurity density, $N'$, for each impurity element. The conductivity mobility can be calculated from this data provided that the percentage of ionized impurities is known. Some details of the method will be discussed and results will be presented. The electron mobility approaches 80 cm$^2$/$V$-sec and the hole mobility 60 cm$^2$/$V$-sec for the highest impurity concentrations. The comparison with the theory is better for $n$ type silicon than it is for $p$ type silicon.

**K5. Effect of Minority Impurities on Impurity Band Conduction in Germanium.*** H. Fritzsche and K. Lark-Horovitz, *Purdue University.*—At small impurity concentrations, small overlap between electron wave functions of impurities, impurity band conduction is possible only if minority impurities produce ionized (unoccupied) majority centers. Thermally activated carriers can then move from occupied to unoccupied majority centers. At large impurity concentrations, strong overlap, the localization of the carriers at impurity centers is removed so that they can migrate through the semiconductor without the presence of minority impurities. The effect of adding minority impurities on the conductivity of an impurity band formed by a constant concentration of majority centers has been studied in both concentration ranges. At low concentrations the impurity band conductivity first increases with increasing degree of compensation $K = N_{min}/N_{maj}$ due to the increase in number of unoccupied majority centers. As $K$ approaches unity the conductivity decreases rapidly because of the decrease in number of occupied majority centers. At large concentrations the conductivity decreases as $K$ is increased because (1) the decrease in carrier concentration and (2) the increase in the number of scattering centers. Thus the two different conduction mechanisms can be distinguished.

* Work supported by the U. S. Signal Corps.

**K6. Impurity Band Conduction in Silicon.*** George A. Swartz.†—Conductivity measurements have been made in impure ($\sim5\times10^{17}$ impurities/cc) $p$ and $n$ type silicon from 90°K to 5°K. Hall effect measurements have been made on the same specimens from 90°K to 17°K. The log $e$ *vs* $1/T$ curve showed a knee in agreement with previous measurements by Morin and Maita[1] and also the log$R$ *vs* $1/T$ curve showed a pronounced peak at about 25°K. Using the data together with the expressions for the Hall coefficient and conductivity for a two carrier model, the conductivity in the "impurity band" was calculated separately from the conductivity in the conduction band. In the case of a sample of $p$ type, boron doped silicon a plot of log "impurity band" resistivity *vs* $1/T$ exhibits a minimum at 25°K and becomes linear below 14°K. A suggested explanation is based on the excited $1s$ states of the impurity atoms proposed by Kohn and Luttinger[2] in $n$ type silicon. Conduction would take place in the "band" formed by the excited $1s$ states instead of in the ground $1s$ state because of the higher mobility resulting from a larger wavefunction overlap in the excited states. As the temperature is lowered charge carriers drop out of the excited $1s$ states and into the nonconducting ground states, making the resistivity exponentially dependent on temperature.

* Research supported by the Office of Naval Research.
† Philco Research Fellow.
[1] F. J. Morin and J. P. Maita, Phys. Rev. **96**, 28 (1954).
[2] W. Kohn and J. M. Luttinger, Phys. Rev. **98**, 915 (1955).

**K7. Pressure Dependence of the Resistivity of Gold Doped Silicon.*** Marshall I. Nathan and William Paul, *Harvard University.*—Gold impurities in silicon introduce two levels into the forbidden energy gap[1]: an acceptor level $E_1$, 0.54 ev below the conduction band minimum $E_c$, and a donor level $E_2$, 0.35 ev above the valence band maximum $E_v$. Properly compensated samples behave as $n$ type with activation energy $E_c - E_1$ or as $p$ type with activation energies $E_1 - E_v$ or $E_2 - E_v$. Neglecting the small change of mobility,[2] measurements of resistivity can be interpreted to give the pressure variation of these activation energies and of $E_c - E_v$.[3] Pressure measurements to 25 000 kg/cm$^2$ at 24°C give a decrease of $|E_c - E_1|$ nearly three times greater than $|E_v - E_1|$. The sum of these two measurements yields a pressure coefficient for the gap of $-2\times10^{-12}$ ev/dyne/cm$^2$. This is in qualitative agreement with

previous measurements in this laboratory.[2] Measurements to 7000 kg/cm² at −78°C give a coefficient of $|E_2-E_v|$ less than $5\times10^{-14}$ ev/dyne/cm². The smaller coefficient of the activation energies relative to the valence band is similar to what has been observed in gold doped germanium in this laboratory.

* Supported by the Office of Naval Research.
[1] C. B. Collins and R. O. Carlson, Bull. Am. Phys. Soc. Ser. II, 1, 127 (1956).
[2] W. Paul and G. L. Pearson, Phys. Rev. **98**, 1755 (1955).
[3] Carlson, Collins, and Gallagher, Bull. Am. Phys. Soc. Ser. II, 1, 128 (1956).

**K8. Nickel in Germanium.** W. W. Tyler and H. H. Woodbury, *General Electric Research Laboratory.*—Germanium crystals containing known concentrations of arsenic have been saturated with nickel by diffusion at 900°C and rapidly quenched to room temperature. Hall coefficient measurements confirm the results reported[1] for crystals grown from a Ni-doped melt. In addition, the presence of doubly-charged Ni sites in compensated samples has been verified by studies of electron mobility. At 900°C the solubility of Ni in Ge (measured in compensated samples assuming $R_H=1/ne$ in determining the As concentrations) is $7.5\times10^{15}$ cm$^{-3}$, appreciably higher than reported by van der Maesen and Brenkman.[2] At this temperature the apparent diffusivity estimated from the time required to saturate samples with Ni is $>10^{-4}$ cm²/sec. Penning's[3] observation that annealing supersaturated samples at 430°C causes the disappearance of the 0.22 ev Ni levels and the appearance of lower activation energy acceptor levels has been confirmed and extended. Both the fast diffusion and the nature of this low temperature annealing will be interpreted in terms of the dissociative diffusion model.[4]

[1] Tyler, Newman and Woodbury, Phys. Rev. **98**, 461 (1955).
[2] F. van der Maesen and J. A. Brenkman, Philips Research Repts. **9**, 225 (1954).
[3] P. Penning, Phys. Rev. **102**, 1414 (1956).
[4] F. C. Frank and D. Turnbull, Phys. Rev. **104**, 617 (1956).

**K9. Solubility of Lithium in Silicon.** E. M. Pell, *General Electric Research Laboratory.*—The solubility of lithium in silicon has been measured as a function of temperature between 600°C and 1400°C. It reaches a maximum atom impurity fraction of $1.1\times10^{-3}\pm8\%$ at 1200°C, which is consistent with a distribution coefficient of $9\times10^{-3}$. Cooling periods were fast enough to prevent lithium loss from the samples during cooling, but at higher temperatures it was not possible to quench rapidly enough to prevent serious precipitation, as revealed by comparing electrical measurements of lithium remaining in solution after cooling with chemical measurements of total lithium content. Total lithium content was determined by flame analysis, with the predominant analysis error imposed by the limit of detectability and estimated at ±20 ppm for our sample size. The resulting solubility agrees with previous electrical measurements[1] at 600°C but departs markedly from them at higher temperatures and, in general, follows the curve predicted from thermodynamic principles.[2,3]

[1] Reiss, Fuller, and Pietruszkiewicz, J. Chem. Phys. **25**, 650 (1956).
[2] C. D. Thurmond and J. D. Struthers, J. Phys. Chem. **57**, 831 (1953).
[3] R. N. Hall (to be published).

**K10. Precipitation of Lithium in Germanium.** F. J. Morin and H. Reiss, *Bell Telephone Laboratories.*—The precipitation of Li in Ge crystals has been studied by Hall effect and conductivity. The Li solution is formed by equilibrating the crystal at an elevated temperature in contact with a Ge-Li alloy, and precipitation is then followed at around room temperature. The fraction of Li remaining in solution after time $t$ satisfies the expression[1] $\exp(-\alpha t^{\frac{1}{2}})$ which assumes spherical diffusion of Li to a constant number of competing nuclei. The predicted dependence of $\alpha$ upon Li diffusivity has been confirmed experimentally. The number of precipitation nuclei increases with equilibration time and finally reaches saturation. The rate at which saturation is attained increases with dislocation concentration, the initial rate per dislocation being constant. Dislocations and surfaces are too far from the bulk of the Li to act as nuclei. Electron bombardment to produce vacancies introduced similar precipitation in a nearly perfect crystal which had failed to precipitate. Those facts suggest that the precipitation nucleus involves a lattice vacancy.

[1] H. L. Frisch (private communication).

**K11. Ionization Energies of Some Impurities in Germanium-Silicon Alloys.*** M. L. Schultz, *RCA Laboratories* (introduced by G. A. Morton).—This paper reports results of the determination of the dependence of ionization energy upon alloy composition for several impurities in germanium-silicon alloys. Ionization energies $E_i$ were obtained from slopes of plots of $\log\sigma$ *versus* $1/T$ at low temperatures and were confirmed, for some samples, by determination of the threshold of impurity photoconductivity. The impurities investigated and the alloy composition (expressed as atom % Si) ranges covered are: gold—0 to 16; copper—0 to 12; indium—60 to 100 and boron—0 to 9. In each case, $E_i$ increaeses with increasing silicon content. For gold, copper, and indium, $E_i$ is a nonlinear function of alloy composition such that the rate of change of $E_i$ with composition undergoes a large and rather sudden increase at an alloy composition characteristic of each impurity. The magnitudes of the changes in $E_i$ are large. For the lowest lying levels of copper and gold, $E_i$ increases by factors of about three over the ranges investigated. The $E_i$ values for indium are intermediate between those for indium in pure germanium and in pure silicon.

* This work has been performed under Contract N6onr-23603.

**K12. Infrared Absorption by Neutral Impurities in Germanium.** N. Sclar, *Allen B. Du Mont Laboratories, Inc.*, and B. Henvis, *Naval Research Laboratories.*—The infrared absorption by an $n$ type germanium specimen containing approximately $10^{16}$ antimony impurities/cm³ has been measured at 4.2°K over the wavelength range 2–40 microns. Beyond about 7 microns, the spectrum of the absorption constant consists of a number of irregularities superimposed onto a 7/2 power dependence of wavelength. These results are analyzed in terms of the absorption by neutral impurities as described by a simple hydrogen model in which the bound electron is ionized to the conduction band. Over the wavelength region measured, the wavelength dependence is accurately described by this model but the experimental absorption exceeds the theoretical value by approximately a factor of two. By correcting the theoretical constant by this factor and assuming that the resulting expression holds up to the long wavelength limit, it is possible to calculate the effect of room temperature blackbody radiation. This analysis shows that although this radiation peaks at about 10 microns, the chief contributions towards the ionization of the neutral impurities comes from wavelengths beyond 25 microns. It is thus predicted that considerable enhancement of the photoconductivity of such material at 10 microns will result from the use of a cooled filter excluding wavelengths beyond 25 microns.

**K13. Infrared Reflectivity and Effective Mass of Holes in Tellurium.*** R. S. Caldwell and H. Y. Fan, *Purdue University.*—Tellurium samples usually show constant reflectivity for wavelengths above 5 micron, 52% and 43%, respectively, for radiations polarized parallel and perpendicular to the $c$ axis. It has been observed that samples of very large carrier concentrations show variations of reflectivity.[1] Measurements have been made on samples with hole concentrations varying from $7\times10^{18}$ to $1.6\times10^{19}$ cm$^{-3}$ with polarized radiations. Pending measurements of absorption, approximate estimates of carrier effective mass have been made by assuming that the variation of reflectivity on the short wavelength side of the

minimum is largely associated with decrease of refractive index. The preliminary values of effective mass obtained are $m_{\parallel}\sim 0.42m$ and $m_{\perp}\sim 0.48m$. Tellurium is known to have a lower resistivity in the direction parallel to the $c$ axis. Measurements on one of the samples gave $\rho_{\perp}/\rho_{\parallel}=1.65$ at 300°K and 1.35 at 77°K. The values may be too high, since the sample consists of several crystals with the same orientation of $c$ axis, therefore, there may be boundary scattering in the perpendicular direction. Accepting $\rho_{\perp}/\rho_{\parallel}>1$, the result $m_{\perp}\lesssim m_{\parallel}$ indicates that the relaxation time is anisotropic.

* Work supported by a Signal Corps Contract.
[1] W. Spitzer and H. Y. Fan, Bull. Am. Phys. Soc. Ser. II, 1, 331 (1956).

**K14. Electrical Properties of Arc Evaporated Carbon Films.** M. D. BLUE* AND G. C. DANIELSON, *Iowa State College.*—Uniform thin films of carbon in the thickness range 100 to 2300 A have been prepared by arc evaporation in vacuum. Evaporation rates were about 50 A/sec. The electrical properties of these films suggest that unannealed arc evaporated carbon had less long-range order and was, therefore, more truly amorphous in structure than any other form of carbon yet obtained. After the films had been heated to 1200°K, however, their properties were similar to ordinary fine particle carbon blacks, apparently as a result of increased ordering. The electrical resistivity of unannealed films followed ohms law, was not photosensitive, and could be well represented in the temperature range 77°K to 300°K by the equation $R=AT^{-b}$, where $b=5$. When the carbon films were heated above room temperature, the resistivity and the exponent $b$ were both decreased substantially. After the films had been annealed at 1200°K, the resistivity was reduced by a factor exceeding 800, and could be best represented, in the temperature range 77°K to 1200°K, by the equation $R=\alpha-\beta T$. The values of the resistivity, temperature coefficient of resistivity, and thermoelectric power of the annealed films were then more nearly in agreement with the corresponding values for ordinary fine particle carbon blacks.

* Present address: University of Paris.

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FRIDAY MORNING AT 9:30

Physical Sciences, Room A-2

(G. P. HARNWELL presiding)

## *Invited Papers*

**L1. The Mass-Energy Relation in Quantum Mechanics.** W. F. G. SWANN, *Bartol Research Foundation.* (30 min.)

**L2. Resonance Fluorescence and Atomic Nuclei.** F. R. METZGER, *Bartol Research Foundation.* (30 min.)

**L3. Momentum Distributions in Nuclei.** WALTER SELOVE, *University of Pennsylvania.* (30 min.)

**L4. Nucleus Forces from Pi-Meson Theory.** ABRAHAM KLEIN, *University of Pennsylvania.* (30 min.)

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FRIDAY MORNING AT 9:30

Houston Hall Auditorium

(K. R. ATKINS presiding)

## *Invited Paper*

**LA1. Spectroscopy of Superconductors in the Far Infrared.** M. TINKHAM, *University of California, Berkeley.* (30 min.)

## *Cryogenics*

**LA2. Hyperfine Coupling in Metallic Cobalt.** M. A. GRACE, C. E. JOHNSON, N. KURTI,* R. G. SCURLOCK, AND R. T. TAYLOR, *Oxford University.*—Using nuclear orientation techniques we have carried out further experiments[1] with improved arrangements, to determine the hyperfine interaction in ferromagnetics. A single crystal of hexagonal cobalt was cooled to 0.04°K and the intensity $W$ of the $\gamma$ rays emitted parallel and perpendicularly to the hexagonal axis by 10 $\mu$curies of $Co^{60}$ present in the sample was measured as a function of temperature. Down to 0.04°K the anisotropy $1-W(0)/W(\pi/2)$ is well represented by $1.0\times10^{-4}(1/T)^2$. This gives $2.3\times10^8$ gauss for the effective magnetic field at the nucleus, produced by the ferromagnetic electrons aligned in domains along the hexagonal axis. Alternatively, assuming a Hamiltonian $\mathcal{H}=AI_zS_z$ we find for $Co^{60}$ $A=2.2\times10^{-20}$°K, as compared with $2.6\times10^{-20}$°K $-4.2\times10^{-20}$°K in various $Co^{2+}$-salts. (The smaller value given in our preliminary report[1] could be explained by unsatisfactory thermal contact between the specimen and the paramagnetic coolant.) The high-temperature tail of the nuclear specific heat in metallic cobalt is given by $CT^2/R=6.3\times10^{-4}$; below 0.5°K the electronic contribution is less than 10%. The relative magnitudes of the hyperfine coupling in the metal and in the salts will be discussed with regard to $s$-electron contribution to ferromagnetism.

* At present on sabbatical leave in the University of California, Berkeley.
[1] Communications, Conférence de Physique des basses températures, Paris, 1955, p. 263.

**LA3. Some Electrical Properties of Uranium, Titanium, and Copper.*** TED G. BERLINCOURT, *Atomics International.*—Hall effect measurements have been carried out on polycrystalline uranium, titanium, and copper between 1.2°K and room temperature. The Hall coefficient *versus* temperature

curves are characterized in all three metals by a weak temperature dependence in the residual resistivity region; a strong temperature dependence in the small angle electron-phonon scattering region; and a weak temperature dependence in the linear resistivity region. Such behavior in a "simple" metal like copper supports the view that the effect of scattering is comparable to the effect of charge carrier concentration even in a "one-band" metal. Values of the Hall coefficient, $R_T$ in units of cm³/coulomb$\times 10^{-6}$, are listed below for three temperatures.

| | $R_{4.2°K}$ | $R_{77°K}$ | $R_{300°K}$ |
|---|---|---|---|
| Uranium | 1.45 | 3.9 | 4.1 |
| Titanium | −4.1 | −0.95 | −0.05 |
| Copper | −6.8 | −6.1 | −5.1 |

The results of low-temperature transverse magneto-resistance measurements on a urnaium single crystal for various orientations will also be reported.

* This work was supported by the U. S. Atomic Energy Commission and the U. S. Air Force.

**LA4. "Size Effect" in Electrical Resistivity Measurements on Single Crystals of Very Pure Tin at Liquid Helium Temperatures.** J. E. KUNZLER AND C. A. RENTON, *Bell Telephone Laboratories.*—Previous observations of the "size effect" in dc resistivity, due to scattering of electrons at the external boundaries of a metallic specimen, have been restricted to films and thin wires. This is because it is necessary to keep the specimen dimensions comparable with the electron mean free path which was less than $10^{-2}$ cm at liquid helium temperatures in the purest materials then available. However, the apparent "size effect" in such specimens may have contributions (from strain, grain size, compositional variations, etc., as well as boundary scattering) that can be avoided with sufficiently pure single crystals. Theory and early work have been reviewed by Sondheimer.[1] The availability of single crystals of very pure tin[2] ($\rho H_c/\rho 0°C \simeq 10^{-5}$) and of precision measuring facilities[3] (capable of measuring small dc voltages accurately to $10^{-9}$ volt) have made possible "size effect" observations on bulk single crystals. Specimens with initial cross sections greater than 10 mm² were reduced in area by etching between successive measurements. The electron mean free path estimated from the "size effects" is about 1 mm.

[1] E. H. Sondheimer, Advances in Phys. **1**, 1 (1952).
[2] From Dr. A. L. Schawlow and Dr. H. E. Bommel, Bell Telephone Laboratories.
[3] J. E. Kunzler and S. E. Haszko (to be published).

**LA5. Electrical Resistivity of $Au_3$ at Low Temperatures.** HIROSHI SATO, *Ford Motor Company.*—$Au_3Cu$ shows anomalous behavior in the electrical resistivity at room temperature in that the ordered alloy has a higher resistivity than the disordered one.[1] Since the temperature coefficients of the resistivity of both alloys are, on the other hand, nearly the same temperature range, this anomalous behavior would give one the impression that even the residual resistance of the disordered state might be lower than that of the ordered state. The resistivities of samples with different degrees of order have been measured between 4°K and 300°K along with experiments directed to elucidate the electronic structure of this alloy. A specimen is first quenched from 600°C in water to obtain the disordered state and then annealed at 185°C for different lengths of time to obtain the ordered state, and the resistivity-temperature curves are taken for each state. It is found that in the region of residual resistance, the resistivities of annealed states are indeed lower than that of the quenched state and, therefore, the resistivity-temperature curves cross each other. The ratios of resistivities at 4.2°K and 298°K turn out to be 0.766 and 0.699 for quenched and well-annealed states, respectively.

[1] M. Hirabayashi, J. Phys. Japan **6**, 129 (1951).

**LA6. $H_c$ *vs* $T$ Curves for Isotopically Enriched Lead Specimens.*** R. R. HAKE, D. E. MAPOTHER, AND D. L. DECKER, *University of Illinois.*—Measurements of the isotope effect in superconducting Pb[1] have been extended to about 1.3°K to study the validity of the "similarity principle" for this element. The data fulfill the expectations of the similarity principle up to critical fields of about 350 gauss. For critical fields greater than this value a marked deviation from "similarity" is observed, the separation between the $H_c$ values for different specimens measured at the same temperature *increasing* sharply as the measuring temperature is reduced. Although the anomalous shift in $H_c$ is in the direction to be expected on the basis of the relative isotopic masses of the specimens, the magnitude is much greater than it should be on the basis of the $M^{\frac{1}{2}}$ dependence which fits the data near $T_c$. Our latest measurements suggest that this anomalous behavior is related to some factor other than the average isotopic mass of the specimen, but, at present, its origin is unexplained.

* Partially supported by the Office of Ordnance Research, U. S. Army.
[1] Hake, Mapother, and Decker, Phys. Rev. **104**, 549 (1956).

**LA7. Low-Temperature Thermal Expansion of Copper.*** R. W. BALLUFFI AND R. O. SIMMONS, *University of Illinois.*—The lattice expansion of high-purity single crystal copper has been measured in the range 8° to 102°K using an oscillating back reflection x-ray diffraction method. The shift of a high Bragg angle (400) reflection was measured at a distance of 78 cm using film. Relative expansions $<1\times 10^{-6}$ were detectable. The results disagree with previous values obtained by a sensitive but not absolute method[1] (capacitor dilatometer) but substantially agree with measurements using a different absolute method[2] (Fizeau interferometer). These data are of interest in the theory of lattice vibrations. Correlation of thermal expansion and specific heat using Gruneisen theory has been used to show both an increase[3] and a decrease[4] in Gruneisen $\gamma$ at lower temperatures, in aluminum and copper, respectively. The present results in agreement with Rubin *et al.*[2] indicate no variation in $\gamma$ outside realistically assigned experimental error (which for example could conceal 20% decrease in $\gamma$ at 40°K where the linear thermal expansion coefficient is about $2.2\times 10^{-6}$ per degree).

* Work supported by the U. S. Atomic Energy Commission.
[1] D. Bijl and H. Pullan, Physica **21**, 285 (1955).
[2] Rubin, Altman, and Johnston, J. Am. Chem. Soc. **76**, 5289 (1954).
[3] Figgins, Jones, and Riley, Phil. Mag. **1**, 747 (1956).

**LA8. Low-Temperature Thermal Conductivity of Copper and Copper Alloys.** ROBERT L. POWELL AND HANS M. RODER.—The thermal conductivities of copper and several of its dilute alloys have been measured between 4° and 120°K. The conductivity of the purest specimen (Asarco, 99.999%) had a maximum at 10°K of about 140 w/cm°K, more than twice as high as any previously measured copper. By assuming (1) that the total electronic thermal resistance of a given specimen consists of two additive terms, due to intrinsic lattice and imperfection scattering, respectively; and (2) that the imperfection scattering resistance is inversely proportional to the temperature; the intrinsic lattice resistance can be calculated. However, tentative results indicate that the two components are not strictly additive in a specimen of very low imperfection scattering. It was also found that the intrinsic resistance varies appreciably with a change of imperfection scattering due to changes in chemical purity. The exponent of the temperature dependence varied from 1.71 to 2.54; the constant coefficient varied from $1.2\times 10^{-4}$ to $3.51\times 10^{-6}$ (in both cases the latter figure refers to the highest purity). Changes in imperfection scattering due to minor changes in physical structure did not appreciably change the intrinsic resistance.

**LA9. Low-Temperature Thermal Conductivity of Polycrystalline Graphite and Boron Nitride.** J. T. MEERS AND J. C. BOWMAN, *National Carbon Company.**—Thermal con-

ductivity measurements of polycrystalline graphite and boron nitride have been made from 20°K to 273°K using an apparatus similar to that used by Tyler and Wilson.[1] A Linde single crystal sapphire rod was measured for the purpose of calibration and good agreement is obtained with the results of Berman.[2] In the temperature range 20–50°K two graphite samples, which were prepared by pyrolytic deposition, exhibit the expected $T^3$ dependence of thermal conductivity predicted by the specific heat. The polycrystalline samples have a dependence which is greater than $T^2$ for this temperature range and the boron nitride shows thermal conductivity behavior similar to graphite.

[1] W. W. Tyler and A. C. Wilson, Jr., Phys. Rev. **89**, 870 (1953).
[2] Berman, Foster, and Ziman, Proc. Roy. Soc. (London) **231**, 130 (1955).

**LA10. Normal Fluid Densities of Dilute Solutions of $He^3$ in $He^4$.*** R. Dean Taylor and J. G. Dash, *Los Alamos Scientific Laboratory.*—The method of Andronikashvili has been employed to determine the density of the normal fluid of solutions containing 3.8, 6.6, and 11.0 mole percent $He^3$ over the range 1.3°K to the lambda transition temperature of each solution. Normal fluid densities, relative to pure $He^4$, are described to within the experimental accuracy by a single analytic equation over the entire range of concentration and temperature studied. This representation may be broken up into a term due to the $He^4$ in solution and one due to the $He^3$. This effective hydrodynamic density of $He^3$ is shown to increase linearly with the density of superfluid present, in qualitative agreement with a model given by Feynman. The solution lambda points are depressed as the $\frac{3}{2}$ power of the mole fraction of $He^4$ present.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

**LA11. Viscosity $\eta_n$ of the Normal Component of Liquid Helium in Narrow Channels.*** K. R. Atkins, *University of Pennsylvania.*—Recent measurements[1] of $\eta_n$ from thermal conduction in channels of width of the order of $10^{-4}$ cm yield values which are in order of magnitude agreement with other measurements above 1.5°K, but do not show a rapid rise between 1.5°K and 1°K. This will be interpreted in terms of the Landau-Khalatnikov[2] theory which predicts that, at 1.1°K, the roton mean free path is about $2\times10^{-6}$ cm, whereas the phonon mean free path is about $5\times10^{-4}$ cm. Thus, in a channel of width $10^{-4}$ cm the roton contribution to the viscosity is normal, but the phonon contribution is diminished by Knudsen effects.

* Supported by the National Science Foundation.
[1] van Groenou, Poll, Delsing, and Gorter, Physica **22**, 905 (1956).
[2] Landau and Khalatnikov, J. Exptl. Theoret. Phys. **19**, 637 (1949).

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Friday Morning at 9:00

Physical Sciences, Room A-1

(L. A. Wood presiding)

## *High-Polymer Physics, III*

### *Invited Papers*

**M1. Configuration and Conformation in Crystalline Polymers.** R. E. Hughes, *University of Pennsylvania.* (45 min.)

**M2. Kinetics of Spherulite Growth in High Polymers.** B. B. Burnett and W. F. McDevit, *E. I. du Pont de Nemours and Company.* (45 min.)

**M3. Theory of Elastic Behavior of Fibrous Polymers.** F. J. Flory, *Cornell University.* (45 min.)

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Friday Afternoon at 2:00

Physical Sciences, Room A-1

(J. D. Perry presiding)

## *High-Polymer Physics, IV*

### *Invited Paper*

**N1. Viscoelastic Phenomena in Crystalline Polymers.** A. V. Tobolsky, *Princeton University.* (45 min.)

### *Contributed Papers*

**N2. Crystallization and the Stress-Strain Properties of Natural Rubber.** K. W. Scott, *The Goodyear Tire & Rubber Company.*—The point of initial detection of crystallinity was studied for a natural rubber gum vulcanizate stretched at various temperatures. The stress-strain properties of this gum vulcanizate at 25 100 and 120°C are almost identical up to 700% elongation, with the inflection point in the stress-strain curve occurring at 300% elongation. The point of initial detection of crystallinity in this work corresponds to the detection within 2 minutes after stretching of 2% crystallinity by an x-ray spectrometer proportional counter technique. The elongations observed for the initial detection of crystallinity at 25 and 100°C are about 480 and 670%, respectively. These results indicate that the inflection point in the stress-strain

curve of crystallizable elastomers may not be directly related to the crystallization phenomenon. These results are pertinent to the question of whether crystallinity is the major factor responsible for the rapid up-swing in the stress-strain curve of crystallizable elastomers.

**N3. Lattice Energy of Crystalline Polyethylene.** FRED W. BILLMEYER, JR., *du Pont Experimental Station.*—The heat of sublimation of linear paraffin chains from the crystalline form to the gas at 0°K was calculated from heats of fusion, heats of vaporization, and heat capacities of solid, liquid, and gaseous hydrocarbons. The heat of sublimation, which is the lattice energy of the crystalline phase of polyethylene, is 1.88 kilocalories per mole of $CH_2$ groups.

**N4. Some Properties of Networks Formed from Oriented Polymer Chains.** D. E. ROBERTS AND L. MANDELKERN, *National Bureau of Standards.*—The isotropic length, the isotropic melting temperature, and the swelling behavior are compared for natural rubber networks formed by the random cross-linking of highly oriented chains and for the usual type of network formed from chains randomly arranged. The oriented state was achieved by a "racking process" and the cross-linking accomplished by $\gamma$-ray irradiation. The ratio of extended length to retracted length was about eleven and cross-linking in the oriented crystalline state was found to be twice as efficient as in the amorphous state. The isotropic length of the networks formed from racked rubber increased by a factor of two and a half in these experiments. At higher cross-linking densities the length is proportional to the square root of the number of cross-links in accordance with the recent theoretical predictions of Flory.[1] Also in accord with theory is the fact that at all levels of cross-linking the isotropic melting temperatures of networks formed from oriented chains are greater than that for the usual networks. The swelling behavior in benzene of the different networks was studied and the quantitative relations between swelling ratio and cross-linking are different in the two cases.

[1] P. J. Flory, J. Am. Chem. Soc. **78**, 5222 (1956).

**N5. Structure of Spherulites as Revealed by Selected-Area Electron Diffraction and Electron Microscopy.** R. G. SCOTT, *E. I. du Pont de Nemours and Company.*—Two-dimensional spherulites in thin films of the 6-6 nylon have been studied by selected-area electron diffraction, bright-field and dark-field electron microscopy. The electron diffraction patterns were found to be comparable to studies using limited area x-ray diffraction. Bright-field electron microscopy using images of unscattered electrons showed the surface morphology of the structures. In dark-field electron microscopy, one uses the scattered electrons of any desired angle and sector to produce a magnified image of the specimen. By using only those Bragg electrons scattered into limited portions of the principal rings, the radial growth and branching of crystallites in spherulites were seen.

**N6. Tridirectional X-Ray Patterns of Oriented Film at Wide and Small Angles.** W. O. STATTON AND GRACE N. GODARD, *E. I. du Pont de Nemours and Company, Inc.*—Drawn, oriented film of polyethylene terephthalate was studied by means of an x-ray diffraction technique in which the x-ray beam was directed in three mutually perpendicular directions: (1) through the film, (2) and (3) in the plane of the film, parallel and normal to the direction of draw. Patterns were obtained in each of these directions for the diffractions occurring at both small and large angles. This combination of patterns provides a picture of the film's physical structure with these parameters: size, orientation, and arrangement of crystallites; extent of amorphous material; shape of microvoids. In this film the crystallites have planar orientation and are 60 A wide in the plane. A long period of 135 A exists in the direction of draw and is comprised of 75 A crystallite length and 60 A amorphous material. There is evidence that the film is composed of lamellae about 30 A thick; these lamellae are stacked in a staggered arrangement such that the crystallites in one lamella are adjacent to the amorphous regions in the lamella below. The small angle diffraction evidence obtained in this study cannot be reconciled with the "coiled ribbon" arrangement recently proposed in the literature to explain off-meridional diffraction spots.

**N7. Theory of Infrared Dichroism of Rubber-Like Polymers.*** RICHARD S. STEIN, *University of Massachusetts.*—A stretched amorphous rubber-like polymer should exhibit infrared dichroism. This may be theoretically calculated using a technique analogous to that used by Kuhn and Treloar to calculate the birefringence of such a polymer. At low elongations, it is predicted that the dichroism should vary linearly with the stress according to the equation,

$$\frac{D-1}{\sigma}=\frac{3}{10}\frac{M_0 z}{\rho N_0 k T},$$

for a vibration having its dipole moment change occurring perpendicular to the statistical segment axis. $D$ is the dichroism, $\sigma$ the stress, $M_0$ the monomer molecular weight, $\rho$ the density, $N_0$ is Avogadro's number, $k$ is Boltzmann's constant, $T$ the absolute temperature, and $z$ is the number of monomer units per segment.

* Supported in part by a contract from the Office of Naval Research.

**N8. Infrared Spectrum of Polystyrene.** S. KRIMM AND C. Y. LIANG, *University of Michigan.*—The infrared spectrum of polystyrene has been obtained in the region of 70 $cm^{-1}$ to 3200 $cm^{-1}$. These data, plus Raman scattering data from the literature, are used to make a complete assignment of the normal modes of the polystyrene molecule. The benzene ring modes have been analyzed in detail in terms of $C_{2v}$ symmetry, and a set of normal vibrations has been proposed. On the basis of previous analyses of benzene and monosubstituted benzenes, and a study of the combination bands, it has been possible to make a fairly satisfactory assignment of all of the benzene ring fundamentals. Assignments of the $CH_2$, CH, and the skeletal modes are made on the basis of previous studies of spectra of high polymers. The interpretation of the spectrum is in agreement with other evidence that the chain configuration is a random one, i.e., that the polymer is amorphous.

**N9. Crystalline Recovery of Quenched Polyethylene.** R. L. COLLINS, *Phillips Petroleum Company.*—The effect of time and temperature on the crystalline recovery of quenched Marlex* 50 polyethylene has been investigated. Quenching thin films in ice water reduced the room temperature crystallinity from a normal value of 93% to 82%. These specimens were maintained at 25, 66.2, and 106.4°C, and the time variation of crystallinity was followed by nuclear spin resonance.[1,2] The crystalline recovery appears to follow the empirical formula, $X=A+B\log t$, where $X$ is the percentage crystallinity and $t$ is the time in hours. The rate, $\dot{X}$, increases with temperature. The temperature dependence of $B$ was computed by assuming the rate to be controlled by diffusion in the amorphous phase. The temperature dependence of diffusion is determined by nuclear spin resonance line width measurements to be exp $\times(-8700/RT)$. The rate is then $\dot{X}=C/t\exp(-8700/RT)$, and $C$, evaluated at 25, 66.2, and 106.4°C, is $2.2\pm1.9$, $1.7\pm0.5$, and $2.1\pm0.2\times10^8$. This agreement is within the probable error, and justifies the assumption of diffusion as the rate-controlling factor. The result is $\dot{X}=2.04\times10^8(1/t)\exp(-8700/RT)$ and $X=A+4.70\times10^8\log t\exp(-8700/RT)$.

* A Trademark of Phillips' family of olefin polymers.
[1] C. W. Wilson, III, and G. E. Pake, J. Polymer Sci. **10**, 503 (1953).
[2] R. L. Collins, Bull. Am. Phys. Soc. Ser. II, **1**, 216 (1956).

FRIDAY AFTERNOON AT 2:00

Museum Auditorium

(J. G. DAUNT presiding)

## *DSSP Symposium on Liquid Helium*

**P1. Liquid Helium in Thin Films and Very Narrow Channels.** K. R. ATKINS, *University of Pennsylvania.* (30 min.)

**P2. Vapor-Pressure Equation for Helium 3.** T. R. ROBERTS, *Los Alamos Scientific Laboratory.* (30 min.)

**P3. Nuclear Resonance Experiments in Liquid Helium 3.** W. M. FAIRBANK, *Duke University.* (30 min.)

**P4. Helium 3—Helium 4 Thermal Rectifiers.** H. A. REICH, *IBM Watson Laboratory.* (30 min.)

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FRIDAY AFTERNOON AT 2:00

Irvine Auditorium

(E. BURSTEIN presiding)

## *Magnetic Effects in Semiconductors and Metals*

**Q1. De Haas-van Alphen Type Oscillations in the Galvanomagnetic Properties of Graphite.** D. E. SOULE, *National Carbon Company.*—De Haas-van Alphen type oscillations were observed in the Hall effect and magnetoresistance measurements made on purified graphite single crystals at 4.2°K with the magnetic field oriented parallel to the hexagonal axis. Two periods were found in both $R$ and $\Delta\rho/\rho_0$. They were approximately $1.9\times10^{-6}$ gauss$^{-1}$ and $1.4\times10^{-6}$ gauss$^{-1}$ representing, apparently, the majority electrons and holes. These periods are roughly equivalent to those found in the susceptibility.[1,2] Only one of these, however, was previously observed in the galvanomagnetic measurements.[3] Also, a phase difference of $\pi$ was observed here between $R$ and $\Delta\rho/\rho_0$ while a value of $\pi/4$ was found before.[2] The low magnetic field, $25 \leq H \leq 1000$ gauss, behaviors of the Hall coefficient at 300°K, 77°K, and 4.2°K have been further corroborated with those reported previously[3] substantiating the existence in graphite of very light holes, and probably light electrons, in addition to the heavier majority electrons and holes.

[1] D. Shoenberg, Trans. Roy. Soc. (London) **245**, 1 (1952).
[2] T. G. Berlincourt and M. C. Steele, Phys. Rev. **98**, 956 (1955).
[3] D. E. Soule, Bull. Am. Phys. Soc. Ser. II, **1**, 255 (1956).

**Q2. Band Structure of Graphite and de Haas-van Alphen Effect.** J. W. MCCLURE, *National Carbon Company.*—The de Haas-van Alphen effect in the magnetic susceptibility of graphite[1] has been interpreted by applying the susceptibility formula for general bands of Lifshitz and Kosevich[2] to the band model of Slonczewski.[3] The majority electrons and holes are responsible for the two periods of oscillation of the susceptibility. The analysis yields information concerning the band structure: (1) the total band overlap is 0.03 ev, (2) the energy difference between the two doubly degenerate bands at the corner of the Brillouin zone[4] is about 0.025 ev, (3) $\gamma_0$ must be larger than about 1.2 ev, and (4) the relation $\gamma_1 = 0.04\gamma_0^2$ holds approximately (where both $\gamma$'s are in ev and correspond to Wallace's[5] notation).

[1] D. Shoenberg, Trans. Roy. Soc. (London) **245**, 1 (1952).
[2] I. M. Lifshitz and A. M. Kasevich, J. Exptl. Theoret. Phys. (U.S.S.R.) **29**, 730 (1955); Soviet Phys. JETP **2**, 636 (1956).
[3] J. C. Slonczewski, Ph.D. thesis, Rutgers University (1955).
[4] J. L. Carter and J. A. Krumhansl, J. Chem. Phys. **21**, 2238 (1953).
[5] P. R. Wallace, Phys. Rev. **71**, 622 (1947).

**Q3. A New Type of Oscillatory Magnetoresistance in Sodium.** J. BABISKIN AND P. G. SIEBENMANN, *U. S. Naval Research Laboratory.*—Magnetoresistance measurements have been made on a thin sodium wire at 1°K in transverse magnetic fields ($H_T$) up to 60 000 gauss. The high purity sodium specimen obtained through the kindness of S. B. Woods, National Research Council, Ottawa, Canada (0.080 mm diameter and 11 mm long) was in a soft glass capillary. After a slight increase to a maximum at ~300 gauss, the magnetoresistance due to surface scattering[1] (which is superimposed upon the slowly increasing bulk magnetoresistance) decreased rapidly. However, before the bulk magnetoresistance predominated completely at ~15 000 gauss, the surface magnetoresistance exhibited a damped oscillatory behavior with minima at ~3500, 8000, and 12 500 gauss. This new oscillation differs completely from the de Haas-van Alphen type in periodicity and damping and is apparently of the type theoretically predicted[2] for thin films in $H_T$. The bulk magnetoresistance tends towards saturation at higher fields. Even with 0.03% resolution in $H$ and in amplitude, there was no indication of a de Haas-van Alphen type of oscillatory magnetoresistance[3] at 60 000 gauss.

[1] G. K. White and S. B. Woods, Phil. Mag. (8) **1**, 846 (1956).
[2] E. H. Sondheimer, Phys. Rev. **80**, 401 (1950).
[3] T. G. Berlincourt and M. C. Steele, Phys. Rev. **98**, 956 (1955).

**Q4. Theory of Cyclotron Resonance Absorption by Conduction Electrons in Indium Antimonide.** RICHARD F. WALLIS, *U. S. Naval Research Laboratory.*—A quantum theory of cyclotron resonance absorption has been developed to provide a basis for interpreting the experimental data for conduction electrons in indium antimonide. It is assumed that the conduction band is a simple band with minimum at $k=0$. Spin interactions are neglected. The energy levels and wave functions of a conduction electron in a constant magnetic field were computed to fourth order using a simplified form of the effective mass equation of Kjeldaas and Kohn.[1] An expression for the absorption coefficient has been calculated to fourth order which incorporates collision broadening using a single relaxation time. The fourth-order terms lead to a series of absorption peaks each being broadened to the low-energy side. The presence of more than one peak is due to the variation with initial state of the energy separation between initial and final states

at $k_z=0$, where $k_z$ is the electron propagation constant in the direction of the magnetic field. The broadening arises from the dependence of this energy separation on $k_z$. Certain fourth-order terms arising from a warping of the conduction band make third harmonics allowed.

[1] Kjeldaas and Kohn, Scientific Paper 60-94439-1-P4, Westinghouse Research Laboratories.

**Q5. Theoretical Optical Absorption Cross Sections for Interband Magneto-Optical Effects in Semiconductors.** F. J. BLATT, *Michigan State University* and *Naval Research Laboratory*, AND R. F. WALLIS AND E. BURSTEIN, *Naval Research Laboratory*.—Transition probabilities have been calculated for vertical optical transitions between valence and conduction band levels subject to orbital quantization by the action of an externally applied magnetic field. It was assumed that the valence and conduction bands are nondegenerate and have extrema at $k=0$. The effective mass approximation, carried out to second order, was used to obtain suitable wave functions which involve Bloch functions at $k=0$ and the familiar wave functions for a free electron in a constant magnetic field. Effects arising from spin-orbit coupling were neglected. The calculations give certain selection rules, polarization effects, and intensity rules which involve the magnetic quantum number $l$. These results sould have fairly general validity even though the simplifications employed preclude strict application to actual semiconductors such as InSb and Ge.

**Q6. Oscillatory Magneto-Absorption of the Direct Transition in Germanium.*** S. ZWERDLING AND BENJAMIN LAX, *Lincoln Laboratory*.—The infrared transmission through single crystal specimens of intrinsic germanium $\sim 4\ \mu$ and $\sim 7\ \mu$ thick displayed oscillatory behavior in dc magnetic fields up to 36 000 gauss, at photon energies in excess of 0.8 ev. The oscillations exhibited definite anisotropy with the magnetic field oriented along the [100], [111], and [110] crystal directions. Each absorption maximum associated with a transition between the various Landau levels in the conduction and valence bands showed linear behavior with photon energy as a function of magnetic field. From this plot the energy gap of the direct transition was evaluated as $0.803 \pm 0.001$ ev at room temperature.[1] The effective mass of the electron in the $\Gamma_2$-conduction band was found to be $\sim 0.042 m_0$. The theoretical prediction from cyclotron resonance[2] is $\sim 0.034 m_0$.

* The research reported in this document was supported jointly by the Army, Navy, and Air Force, under contract with the Massachusetts Institute of Technology.

[1] W. C. Dash and R. Newman, Phys. Rev. **99**, 1151 (1955) quote 0.81 ev at 300°K.

[2] Dresselhaus, Kip, and Kittel, Phys. Rev. **98**, 368 (1955).

**Q7. Oscillatory Magneto-Absorption in InSb and InAs.†** BENJAMIN LAX, S. ZWERDLING, AND LAURA M. ROTH, *Lincoln Laboratory*.—Transmission in fields up to 36 000 gauss through polycrystalline InSb and InAs of $\sim 10\ \mu$ and $\sim 36\ \mu$ thick, respectively, displayed oscillations at photon energies above the energy gap.[1] The behavior of the two prominent absorption maxima which occur for InSb from 5–7 $\mu$ suggest direct transitions between the conduction and small mass valence bands.[2] (This contrasts with Ge, where the first maximum represents a transition between the conduction and large mass valence bands.) The shift of the first maximum with magnetic field gives $\sim 0.17$ ev for the room temperature direct transition gap, and a small hole effective mass[2] of $\sim 0.02 m_0$. Less intense absorption peaks perhaps associated with indirect transitions were also observed in InSb. For InAs, oscillations were observed from 3–3.5 $\mu$. Only the first maximum was resolved due to sample thickness. Experimental results on very thin samples of InAs and oriented single crystals of InSb will also be presented.

† The research reported in this document was supported jointly by the Army, Navy, and Air Force under contract with the Massachusetts Institute of Technology.

[1] Oscillatory magnetoabsorption was reported concurrently by E. Burstein for InSb and by Benjamin Lax for Ge, at the Semiconductor Symposium, Washington, D. C., October, 1956.

[2] E. O. Kane predicted a small hole mass of $0.015 m_0$. Bull. Am. Phys. Soc. Ser. II, **1**, 299 (1956).

**Q8. Theory of the Oscillatory Magneto-Absorption in Semiconductors.*** LAURA M. ROTH, BENJAMIN LAX, AND S. ZWERDLING, *Lincoln Laboratory*.—The theory of the oscillatory effects of the optical magneto-absorption in semiconductors has been studied, using the effective mass approximation. For two simple bands separated by an energy gap and having masses $m_c$ and $m_v$, the absorption consists of a series of maxima separated by an energy $\Delta E = (heH/c)[(1/m_c)+(1/m_v)]$. The selection rule for direct transitions in $\Delta n=0$, $\Delta k_{y,z}=0$, where $n$ is the quantum number for the Landau levels in each band and $k_{y,z}$ are the wave number components for the particular gauge used. For a complex valence band such as that of germanium, the situation is more involved, and the theory of Luttinger and Kohn[1] as modified by Luttinger[2] was used. The results predict: (1) unequal spacing of levels for low quantum numbers, as observed experimentally,[3] (2) fine structure of the absorption maxima which should be resolvable at low temperatures, (3) anisotropy of absorption maxima. The theory will be compared with experiment for germanium, and the principles will also be applied to InSb and InAs.[3]

* The research reported in this document was supported jointly by the Army, Navy, and Air Force, under contract with the Massachusetts Institute of Technology.

[1] J. M. Luttinger and W. Kohn, Phys. Rev. **97**, 869 (1955).

[2] J. M. Luttinger, Phys. Rev. **102**, 1030 (1956).

[3] S. Zwerdling and B. Lax; Lax, Zwerdling, and Roth (preceding abstracts).

**Q9. Mobility of Electrons in Magnetically Produced Impurity Bands.** R. J. SLADEK, *Westinghouse Research Laboratories*.—Application of a strong magnetic field to $n-$InSb at liquid helium temperatures lowers some of the electronic energy states below the conduction band. Evidence that some electrons leave the conduction band and go, presumably, into such impurity states has been found experimentally as a sharp increase in Hall coefficient with magnetic field strength at high fields. In addition, a maximum occurs in the Hall coefficient as a function of temperature for a fixed, strong magnetic field indicating that electrons in impurity states have a finite mobility.[1] In order to determine the mobility of these impurity band electrons, we have measured the electrical resistivity and Hall effect as a function of temperature and magnetic field strength up to 28 000 gauss in several $n$-type InSb samples. Our results indicate that the impurity band electron mobility varies as $\exp[-r_s^3/2a_\perp^3]$ where $r_s$ is $\frac{1}{2}$ the spacing between donors and $a_\perp$ is the radius, perpendicular to the magnetic field, of the wave function of an electron localized around a donor ion as given by the theory of Yafet, Keyes, and Adams.[2]

[1] R. J. Sladek, Bull. Am. Phys. Soc. Ser. II, **1**, 332 (1956).

[2] Yafet, Keyes, and Adams, Internatl. J. Phys. Chem. Solids **1**, 137 (1956).

**Q10. Magnetoresistive Behavior of PbS, PbSe, and PbTe.** ROBERT S. ALLGAIER, *U. S. Naval Ordnance Laboratory and University of Maryland*, AND WAYNE W. SCANLON, *U. S. Naval Ordnance Laboratory*.—We have studied the magnetoresistance of about 15 samples of PbS, PbSe, and PbTe at 77.4°K and 4.2°K. The sample current was parallel to a cubic axis in all cases. At 77.4°K the samples closely followed the phenomenological small field theory; i.e., the resistance change was proportional to $H^2$, and for constant magnetic field varied as $\sin^2\theta$, $\theta$ being the angle between sample current and field. At 4.2°K, saturation occurred at about 2000 gauss in several samples, and unusual effects appeared in the angular behavior.

At both temperatures the longitudinal magnetoresistance was generally larger than the transverse, 4 times larger in some cases. Because of the high mobility values (as high as 750 000 cm²/v-sec) occurring in the samples at 4.2°K, the resistance change in some cases was several times as large as the zero field resistance, despite the fact that the samples are highly degenerate at this temperature.

**Q11. Effects of Ionized Impurity Scattering on the Magnetoresistance in Germanium.*** R. K. WILLARDSON AND A. C. BEER, *Battelle Memorial Institute.*—The transverse magnetoresistance effect is analyzed in the region where the scattering mechanism involves both lattice vibrations and ionized impurities. The doubly degenerate valence band model is used, with neglect of the warping of the heavy mass band. Effects of anisotropy are investigated by using an ellipsoid model representative of the conduction band. Results are given in terms of impurity scattering parameters, $\beta \equiv \alpha\mu_L/\mu_I$, representative of each band. The factor 6, often used in impurity scattering formulas and obtained by maximizing the nonlogarithmic factor in the integrand of the conductivity transport integral in the limit of impurity scattering only, is replaced by $\alpha$. This parameter is then determined separately[1] for each value of $\mu_L/\mu_I$ as well as for the Hall and the conductivity transport integrals. Results are compared with data for specimens with acceptor concentrations ranging from $10^{13}$ to $10^{18}$/cm³ and at temperatures between 50 and 300°K. Experimental mobility values were obtained using the strong magnetic-field limits of the Hall coefficients and the zero-field conductivities.

* This research was supported by the U. S. Air Force, through the Office of Scientific Research of the Air Research and Development Command.

[1] R. Mansfield, Proc. Phys. Soc. (London) **B69**, 862 (1956).

**Q12. The Effect of Impurity Scattering on the Magnetoresistance of Germanium.** MAURICE GLICKSMAN, *RCA Laboratories.*—Measurements of magnetoresistance and Hall effect have been made on samples of germanium of varying impurity concentrations and at different temperatures so that the scattering ranged from almost all due to the lattice to almost all due to ionized impurities. If the data in the low-field region are analyzed, using the known band structure, to calculate $W=(m_l/m_t)(\tau_t/\tau_l)$,[1] we find that $W$ decreases as the impurity scattering becomes dominant. We find $W=12$ for $\mu/\mu_L \approx 1$, decreasing to $W=3$ for $\mu/\mu_L=0.08$. This variation is to be expected for the anisotropic impurity scattering calculated by Ham.[2]

[1] C. Herring and E. Vogt, Phys. Rev. **101**, 944 (1956).
[2] F. Ham, Phys. Rev. **100**, 1251(A) (1955).

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## FRIDAY AFTERNOON AT 2:00

## Physical Sciences, Room A-2

## (W. F. G. SWANN presiding)

### *Nuclear and Theoretical Physics*

**R1. Conversion Efficiency of Scintillation Phosphors.*** W. J. VAN SCIVER AND L. BOGART, *Levinthal Electronic Products, Inc.*—Conversion efficiencies (emitted useful light energy divided by exciting particle energy) have been reported[1] for several scintillation phosphors. Variations in results (e.g., 1% to 10% for anthracene) indicate the desirability of a more reliable measuring procedure. A method which has given accurately repeatable results uses (1) a calibrated thermopile and monochromator to measure photomultiplier cathode sensitivities and (2) a light pulser tube and an electrometer to determine photoelectrons per scintillation pulse. In the latter step an RCA C-73687 light pulser tube is substituted for the phosphor in a typical scintillation counter setup. Its intensity is adjusted to give pulse height equivalent to that of the $Cs^{137}$ photopeak. Finally the photomultiplier cathode current is measured with the electrometer. The current divided by pulse rate is photocathode electronic charge per pulse. Combination of this value with cathode efficiency and primary particle energy yields the phosphor's conversion efficiency. For a 1 in. ×1 in. Harshaw NaI(Tl) crystal with MgO smoked reflector and DC200 fluid optical coupling the value 14.1±0.7% is obtained.

* This work was supported in part by the U. S. Atomic Energy Commission.

[1] R. Hofstadter and J. McIntyre, Phys. Rev. **78**, 617 (1950); **80**, 631 (1950); J. I. Hopkins, Rev. Sci. Instr. **22**, 29 (1951); F. B. Harrison, Nucleonics **10**, No. 6, 40 (1952); Furst, Kallmann, and Kramer, Phys. Rev. **89**, 416 (1953); J. B. Birks and M. E. Szendrei, Phys. Rev. **91**, 197 (1953).

**R2. Speculation on Mechanism of Bubble Chamber.** FREDERICK SEITZ, *University of Illinois.*—The operation of the bubble chamber appears to be related to the processes of radiation damage in solids. Under the conditions of superheating normally employed for the hydrocarbons the critical bubble diameter is near $10^{-6}$ cm. Three components of energy enter into the formation: (1) surface energy; (2) heat of sublimation of contained gas; (3) work to push back liquid rapidly. Each of these terms appears to be of the order of 1 kev under the conditions described by Glaser *et al.*[1] Thus the bubbles presumably should be associated with electron or displacement spikes involving a threshold energy near 1 kev. Displaced electrons and atoms having energies near this limit behave similarly, the former losing energy by electron excitation, the second by Coulomb encounters with nuclei, initially under conditions of moderately weak screening. The ranges are comparable, although angular scattering is very large and probably very important for localization of energy. Since electron excitation by charged incident particles is much more probable than atomic displacement for a given threshold enegry, it appears most likely that the overwhelming fraction of bubbles is related to electron excitation. The threshold energy is much lower for liquid hydrogen than for a typical hydrocarbon.

[1] D. A. Glaser and D. C. Wahm, Phys. Rev. **97**, 474 (1955); Glaser, Wahm, and Dodd, *ibid.* **102**, 1653 (1956).

**R3. Low-Energy Pi Mesons Associated with High-Energy Events.*** A. G. BARKOW AND B. CHAMANY, *Marquette University.*—Two high-energy events accompanied by low-energy $\pi$ mesons were found in cosmic-ray plates. One event is the breakup of either $N_7$ or $O_8$ into three alpha particles and a proton of energies around 1 Bev/nucleon, and a $\pi^+$ meson of energy 8.1 Mev. In the c.m. system the $\pi^+$ meson is projected backwards with an energy of 200 Mev, while the energies of the other particles were less than 5 Mev/nucleons. The second event is a possible alpha-nucleon interaction resulting in a jet consisting of 9 mesons, one $\pi^0$ and one photon producing

electron pairs, three low-energy $\pi$ mesons, two of which are $\pi^-$ and one is a $\pi^+$, and three protons. Preliminary measurements by scattering and grain count indicate energies greater than one Bev for the mesons, and 3–25 Mev for the low-energy mesons. Results of angular distribution measurements[1] in the center-of-mass system will be reported.

* Work supported by the National Science Foundation.
[1] Debenedette, Garelli, Tallone, and Vigone, Nuovo cimento **4**, 1142 (1956).

**R4. Gamma Rays of $As^{77}$.*** V. S. Dubey† and C. E. Mandeville, *Bartol Research Foundation*.—The quantum radiations of $As^{77}$ have been re-examined by scintillation counting methods. The previously reported soft radiations near 30 kev are indeed found to be a bremsstrahlung effect as recently noted.[1] By careful coincidence measurements, a gamma ray of energy 280 kev is shown to be definitely present in the disintegration scheme.

* Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
† On leave of absence from Agra College, Agra, India.
[1] H. Langevin, J. phys. et radium **16**, 238 (1955).

**R5. $Q$-Value Measurements for Chlorine and Aluminum.*** W. C. Porter, M. A. Rothman, and D. M. Van Patter, *Bartol Research Foundation*.—Nuclear reaction energies have been measured using a double-focusing magnetic spectrometer. The major source of error for the previous determinations of the $Cl^{35}(p,\alpha)S^{32}$ and $Cl^{37}(p,\alpha)S^{34}$ ground-state $Q$ values made at this laboratory[1] was associated with a nonlinear calibration curve for the spectrometer. This nonlinearity has been reduced by a factor of $\geq 4$, and the two reaction energies have been remeasured as $1.860\pm0.005$ and $3.028\pm0.006$ Mev, in better agreement with the M.I.T. results.[2] As a check on the reliability of the determinations, two $Al^{27}(p,\alpha)Mg^{24}$ groups were observed, with measured $Q$ values of $1.596\pm0.006$ and $0.230\pm0.005$ Mev, corresponding to the ground state of $Mg^{24}$ and the first excited state at $1.366\pm0.006$ Mev. A further check was provided by the observation of six $Al^{27}(p,p')Al^{27}$ inelastic groups, corresponding to $Al^{27}$ levels at $0.842\pm0.003$, $1.013\pm0.003$, $2.205\pm0.004$, $2.727\pm0.004$, $2.975\pm0.004$, and $2.998\pm0.004$ Mev. All these results appear to be in good agreement with previous measurements.[3]

* This research was supported by the U. S. Air Force, through the Office of Scientific Research of the Air Research and Development Command.
[1] Van Patter, Swann, Porter, and Mandeville, Phys. Rev. **103**, 656 (1956).
[2] Endt, Paris, Sperduto, and Buechner, Phys. Rev. **103**, 961 (1956).
[3] Dunahue, Jones, McEllistrem, and Richards, Phys. Rev. **89**, 824 (1953); Browne, Zimmerman, and Buechner, *ibid.* **96**, 725 (1954).

**R6. Photoneutron Reactions in $F^{19}$ and $N^{14}$ Near Threshold.** W. L. Bendel, *Naval Research Laboratory*.—In order to check the validity of equating $Q$-values of photoneutron reactions to observed thresholds, corrected to the center-of-mass system, we have irradiated two elements with similar threshold energies. Hollow cylinders of Teflon and melamine were bombarded with 10.2- to 11.3-Mev bremsstrahlung from the NRL 22-Mev betatron. The $F^{18}$ and $N^{13}$ activities were detected with a cylindrical Geiger counter, surrounded by an anticoincidence ring of counters to reduce the background. The photoneutron threshold of nitrogen was found to be $155\pm25$ kev above that of fluorine. Mass tables[1] indicate a difference of 143 kev. The fluorine activation curve shows a sharp break $72\pm20$ kev above threshold. This break corresponds to a $F^{19}$ level about 69 kev[2,3] above threshold, observed in the $O^{18}(p,n)F^{18}$ reaction. We conclude that the observed thresholds are the $Q$ values for these reactions.

[1] J. Mattauch *et al.*, Ann. Rev. Nuclear Sci. **6**, 179 (1956).
[2] H. Mark and C. Goodman, Phys. Rev. **101**, 768 (1956).
[3] H. A. Hill and J. M. Blair, Phys. Rev. **104**, 198 (1956).

**R7. Electron Mass as the Natural Unit of Mass for Nuclei.** Enos E. Witmer, *University of Pennsylvania*.—The most accurate atomic masses appear to be those published in three articles in 1956 by Quisenberry, Scolman, and Nier. These seem much better than those obtained from nuclear reaction energies. If we supplement these tables with four values calculated from those of Quisenberry *et al.* by atomic mass differences taken from the tables made from nuclear reaction energies and one value, $Li^7$, taken from the latter tables, we can show that the nuclear masses of $Li^7$, $Be^{10}$, $C^{11}$, $C^{12}$, $O^{15}$, $F^{17}$, and $Mg^{26}$ are remarkably close to integers in terms of the rest mass of the electron, $m$, provided $m$ is 0.000 548 771 241 amu. The nuclear mass of $Zn^{67}$ is $(121\,967.037\pm0.013)m$. Although this value is not remarkably close to an integer, future measurements might bring it into that category. The most accurately measured of these nuclear masses, such as $H^1$, $B^{10}$, $N^{15}$, $O^{16}$, and $O^{17}$ are integral multiples[1] of $m/256$ within the limits of present accuracy. In addition a small number of nuclear reaction energies that are measured accurately enough to test the latter idea seem to be in harmony with it.

[1] E. E. Witmer, Phys. Rev. **93**, 667 (1954); **95**, 610 (1954).

**R8. Use of a General Virial Theorem with Perturbation Theory.** W. J. Carr, Jr., *Westinghouse Research Laboratories*.—If the Hamiltonian of a system is broken up into a series of homogeneous operators in the space coordinates, the sum of their mean values multiplied by the degree of homogeneity equals zero for a bound state. Assume that the Hamiltonian contains three groups of homogeneous terms: for example, kinetic energy, Coulomb energy and a third interaction, $U$, which is small. By the "virial" theorem, the energy can be expressed in the mean values of any two of these terms. From perturbation theory, another relationship is derived which allows various orders of the energy to be obtained from the mean value of any one of the three terms of the Hamiltonian. The perturbation relation is $\bar{U}=\Sigma nE_n$, where $E_n$ is the $n$th-order correction to the energy, defined by $E=\Sigma E_n$.

**R9. Generalization of Good's Hamiltonian Formalism for Fields.** Hans Freistadt, *Newark College of Engineering*.—A canonical formalism for relativistic field theory is proposed, in which the Hamiltonian density is a tensor of second rank rather than a scalar. The formalism is otherwise very similar to that of Good,[1] over which it has some formal advantages, especially in the construction of quantum mechanical Poisson Brackets. As an illustration, the free Klein-Gordon and Dirac fields are worked out.

[1] R. H. Good, Jr., Phys. Rev. **93**, 249 (1954). Just before submitting this abstract, the author received a letter, hereby gratefully acknowledged, from which it is evident that Good had already developed this formalism (in some ways further than the present author, though without considering quantization) but unfortunately had not published it.

***Post-Deadline Papers, If Any***

FRIDAY AFTERNOON AT 2:00

Houston Hall Auditorium

(W. T. READ presiding)

## *Dislocations and Allied Topics*

**RA1. Effect of Cold Work on the Spectral Reflectivity of CsCl-Type Alloys.** L. MULDAWER, *Temple University and Ford Motor Company.*—Many CsCl structure alloys are normally strongly colored but tend toward silver-gray upon cold working. The normal color is regained as a function of time even when the specimen is not in contact with air. This color recovery is presumably associated with the mechanical recovery of such alloys which occurs at room temperature. Spectral reflectivity curves show that cold working is similar to increased temperature in some respects. In $\beta$-brass, the reflectivity minimum disappears, the steepness of the reflectivity edge lessens, and the difference in reflectivity on either side of the edge decreases. Similar effects are seen with $\beta$-AgZn, $\beta$-AgCd, and $\beta$-AuZn. Inasmuch as the strain produced by cold work is extremely inhomogeneous, it should be expected that the reflectivity edge would be smeared out. The possible nature of this effect will be considered.

**RA2. Dislocation Densities in Super Pure Aluminum.** L. VASSAMILLET AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.**—Density of dislocations can be determined by studying the detailed structure and shape of monochromatic diffraction spots.[1] This method has been applied to a study of the nature of cold work introduced in single crystals of super pure aluminum (99.9999+%) by a machining operation. The density of dislocations has been measured as function of distance from the surface and its change during the process of annealing has been observed. A speculation is made as to the mechanism of deformation and as to the array of dislocations thus introduced. The relative amounts of screw and edge components are estimated and the results are compared with internal damping studies made by Mr. Chambers on the same crystals (see following abstract).

* Research supported by a U. S. Atomic Energy Commission contract.
[1] Lambot, Vassamillet, and Dejace, Acta Metallurgica 1, 711 (1953) and 3, 150 (1955).

**RA3. Dislocation Damping on 99.99% Pure and Zone-Refined Aluminum Single Crystals.** R. SMOLUCHOWSKI AND R. H. CHAMBERS.*†—Single crystal damping samples were made from 99.99% pure aluminum and from aluminum which was zone-refined (by W. Tiller of the Westinghouse Research Laboratories). Perfection of the heavily etched crystals was determined by L. Vassamillet by x-rays (see preceding abstract). Kilocycle internal friction and Young's modulus of the two sets of crystals was measured as a function of amplitude and thermal history. Granato-Lücke[1] plots show deviation from theory at low strain amplitudes and a reasonable fit for amplitudes between $5\times10^{-7}$ and $5\times10^{-6}$. The fit is remarkably good in the zone-refined aluminum considering the very small impurity concentration. Zone-refined aluminum, however, shows much poorer fit above $5\times10^{-6}$ than is found in the 99.99% aluminum; it gives also a larger dislocation loop length than the 99.99% aluminum, as is to be expected. In both cases the dislocation density appears to be several orders of magnitude smaller by comparison with values for relatively undeformed crystals.

* National Carbon Fellow, 1951–1955.
† Supported in part by a U. S. Atomic Energy Commission research contract.
[1] A. Granato and K. Lücke, J. Appl. Phys. 27, 583 (1956).

**RA4. Time-Dependent Damping Phenomenon in Magnesium and Aluminum Single Crystals.** R. H. CHAMBERS* AND R. SMOLUCHOWSKI, *Carnegie Institute of Technology.*†—Observations have been made of time-dependent kilocycle internal damping in 99.99% pure magnesium, aluminum and zone-refined aluminum single crystals. For a constant strain amplitude, the decrement $\delta$ and apparent Young's modulus change with time if the amplitude exceeds values for which the decrement and modulus begin to show amplitude dependence. If the oscillation is stopped and observations made either at lower amplitudes or rapidly—several seconds per measurement—at the original amplitude, the decrement returns slowly to the original value. The recovery curve follows $\delta-\delta_0=A\times\exp(-Bt^n)$, where $n$ is 0.4 to 0.6 depending upon the material. Parameters $A$ and $B$ show temperature and amplitude dependence which will be discussed. Granato-Lücke plots of the amplitude dependence show that the impurity loop length is lengthened during excitation and shortened during recovery. Zone-refined specimens show evidence of the time dependence, but the effect is considerably smaller. These results are interpreted in terms of the production of vacancies produced as the edge components of dislocations break away from the pinning impurities and the subsequent loss of these impurities by radial diffusion from their pinning positions.

* National Carbon Fellow, 1951–1955.
† Supported in part by a U. S. Atomic Energy Commission research contract.

**RA5. Dislocation Helices.*** PETER GIBBS, *University of Utah.*—It has been proposed[1] that, because of climb, and edge-type Frank-Read dislocation generator would bulge into that plane normal to the Burgers vector which contains the nodes—and, with sufficient vacancies, could generate dislocation rings in this plane. It is proposed here that a shear stress which would displace one Frank-Read node in the slip direction relative to the other node causes this bulging dislocation to pass into a helix. At reasonable temperatures, dislocation motion in the direction of the helical axis can occur by vacancy absorption, or by the diffusion of vacancies along the dislocation. Thus, it is possible to join up successive helical turns and detach a dislocation ring.

* Office of Naval Research support.
[1] Bardeen and Herring, *Imperfections in Nearly Perfect Crystals*, Shockley *et al.*, editors (John Wiley and Sons, Inc., New York, 1952). See reference 17 there.

**RA6. Dislocation Mobilities in LiF.** W. G. JOHNSTON AND J. J. GILMAN, *General Electric Research Laboratory.*—Mobilities of individual dislocations in LiF have been investigated using multiple etching techniques. The stress required to move a newly created dislocation, $\sigma_m$, is very nearly two-thirds the macroscopic critical shear stress, $\sigma_y$, over a range of $\sigma_y$ from 300 to 400 g/mm$^2$. $\sigma_y$ is varied by heat treatment, neutron irradiation, and by varying the test temperature. The close relationship between $\sigma_m$ and $\sigma_y$ implies that the flow stress of the crystals is determined by the lattice resistance to dislocation motion. The dislocation density is low ($5\times10^4$ cm$^{-2}$), so dislocation mobility is not determined by interaction between dislocations. New dislocations have been introduced prior to neutron irradiation, and afterward the stress required to move the same dislocations is greater than $\sigma_y$, so that the irradiated dislocations do not take part in the deformation. When newly created dislocations are aged, $\sigma_m$ increases, eventually

exceeding $\sigma_y$, so that the aged dislocations do not move when the crystal is bent. It appears that glide dislocations can be pinned securely enough so that they do not take part in the deformation process.

**RA7. Origin of Glide Dislocations in Crystals.** J. J. GILMAN AND W. G. JOHNSTON, *General Electric Research Laboratory.*—By means of the authors' etching technique, it has been found that (110) [1$\bar{1}$0] glide dislocations can be nucleated in LiF crystals at low stress levels. The dislocations are nucleated as loops in regions of the crystals which previously did not contain dislocations. Nucleation is caused (a) by stresses at the tips of slowly moving cracks, (b) by stresses under balls pressed lightly onto crystals, (c) by thermal stresses due to moderate cooling rates from 400°C and above, and (d) by stresses during plastic bending. Except in case (a) the stresses are known. The nucleation stress in all cases is of the order of 1 kg/mm$^2$ which is also the macroscopic yield stress. Because of the low nucleation stress, most of the deformation of these crystals is caused by dislocations which nucleate directly from the crystal and do not come from Frank-Read courses. Although some F-R sources may be present and operative, they are unnecessary and play only a minor role. The nature of the present nucleation process is known. It may involve defects other than dislocations, but there is but little evidence on this point.

**RA8. Etch Hillocks on Germanium Single Crystals.** B. W. BATTERMAN AND W. G. PFANN, *Bell Telephone Laboratories.*—Etch hillocks have been observed on germanium single crystal surfaces exposed to a superoxol etchant.[1] Hillocks appear on surface orientations in the region about a [110] zone circle lying between two adjacent [111] poles. On the zone circle itself, the hillocks are symmetrical about the (110) plane and form hexagonal pyramids on a (1$\bar{1}$0) surface. The plane surfaces bounding the hillocks have orientations close to (322) and (310). Etch pits ascribed to dislocations are found only on surfaces within approximately 7° of [100] and [111]. Hillocks do not form within this range about [111]. Hillocks do not correspond to dislocations. The etch rate of orientations throughout the stereographic triangle has been measured. Correlation between observed orientation-dependent etch rate and formation of hillocks and etch pits will be discussed.

[1] 1:1:4 volume parts of $H_2O_2$ (30%), HF (49%), and $H_2O$, respectively.

**RA9. Precipitation of Impurities on Dislocations in Silicon.** W. C. DASH, *General Electric Research Laboratory.*—The technique developed for decorating dislocations in silicon by diffusion and observation of precipitates with an infrared image tube first used with copper[1] has been used to study diffusion and precipitation in silicon of a number of other impurities including Fe, Co, Ni, Zn, Au, Ag, Pt, Mn, and U. Precipitation of all these elements occurs on dislocations in patterns very similar to that of copper, although the details of the heat treatment required for decoration vary from one element to another. In addition, a part of the aggregation of oxygen identified by Kaiser and Keck[2] in crystals grown from quartz crucibles following long heat treatment at about 1000°C is found to occur at dislocations. In this case no decoration can be seen by infrared transmission. The method of observation involves sectioning and etching, resulting in the delineation of dislocation arrays by rows of etch pits.[3]

[1] W. C. Dash, J. Appl. Phys. **27**, 1193 (1956).
[2] W. Kaiser and P. H. Keck, Bull. Am. Phys. Soc. Ser. II, **1**, 321 (1956).
[3] A similar method for identifying dislocations in Al–Cu alloys was reported by H. Wilsdorf and D. Kuhlmann—Wilsdorf, Report on the Conference on Defects in Crystalline Solids, University of Bristol, p. 175 (1954).

**RA10. Dislocation Contribution to the Self-Diffusion Coefficient in Metals.** EDWARD W. HART, *General Electric Research Laboratory.*—It is readily shown that, under usual circumstances, the randomly distributed dislocations in a metal single crystal will contribute to the self-diffusion of the metal atoms. The contribution is like that of a volumetric diffusion coefficient and for ordinary experimental techniques is not distinquishable from the diffusion contribution by the matrix proper. It is estimated that at the lowest temperatures for which single crystal diffusion measurements have been made this contribution is of the order of 10% of the bulk contribution in agreement with the observed small enhancement. At slightly lower temperatures this contribution can easily be a much larger fraction of the diffusion coefficient.

**RA11. Effect of Quenching on Yield Stress of Pure Gold.*** J. W. KAUFFMAN AND M. MESHII, *Northwestern University.*—Samples of 99.999% gold polycrystalline wires were quenched and slow cooled from 900°C and were deformed at room temperature. After annealing in the range room temperature to 100°C subsequent to quenching the yield stress increased markedly over that for slow cooled specimens. No increase was found immediately after the quench, but the yield stress was found to increase with annealing, finally reaching a stable saturation value of about a factor of two over the initial value. Anneals were carried out at various higher temperatures on quenched samples in which the yield stress had reached its saturated value. A one-hour anneal at 700°C was needed for complete softening. Preliminary data have been obtained on the rates of increase of yield stress at various temperatures between room temperature and 100°C; these give an energy of motion for defects between 0.6 ev and 0.8 ev, in agreement with values[1,2] obtained from the recovery of electrical resistivity in quenched gold.

* This work was partially supported by the U. S. Atomic Energy Commission.
[1] J. W. Kauffman and J. S. Koehler, Phys. Rev. **97**, 555 (1955).
[2] Bauerle, Klabunde, and Koehler, Phys. Rev. **102**, 1182 (1956).

**RA12. Room Temperature Annealing of Quenched Gold.** J. E. BAUERLE AND J. S. KOEHLER, *University of Illinois.**—99.999% pure gold wires quenched from below 750°C show the following behavior during annealing at 60°C. Over 99% of the resistance quenched in anneals out at that temperature. The annealing follows first-order kinetics. The time for the quenched in resistance to drop to half its initial value was 19.5 hours for a quench from 700°C and 50 hours for a quench from 600°C. Simultaneously measured length and resistivity changes were proportional after a 700°C quench. The fractional length changes multiplied by $1.1\times10^{-3}$ ohm cm give the resistivity changes. The energy of motion measured after a 700°C quench was $0.72\pm0.05$ ev. Wires quenched from above 750°C showed more complex annealing. Initially the annealing rate was consistent with the rates mentioned above, then an increase in rate occurred. After an 800°C quench the half decay time at 40°C was 49 hours and the energy of motion $0.66\pm0.03$ ev. After a 900°C quench the half-time was 3¼ hours at 40°C and the energy of motion was $0.63\pm0.05$ ev. Length and resistivity changes were again proportional (same constant). Deformation produces an increase in rate only in the initial slow portion of the annealing.

* Partially supported by the Office of Ordnance Research.

**RA13. Interpretation of Quenching Experiments on Gold.** J. S. KOEHLER AND J. E. BAUERLE, *University of Illinois.**—Three observations lead to the conclusion that there is not an appreciable amount of divacancy formation from single vacancies at room temperature or during quenching. First the annealing at room temperature is first order after a quench from below 750°C; it can be described quantitatively by supposing that dislocations maintain the region near their core at the equilibrium value so that after quenching vacancies diffuse to dislocations and die there. Second, the observed quenching times required to retain defects (i.e., 10 to 50 milliseconds) are

consistent with vacancy diffusion to dislocations and not with the times required for vacancy recombination. Third, Meechan and Brinkman find a prominent room temperature annealing process in copper irradiated with 1.25 Mev electrons. Calculations show that the ratio of the number of single to divacancies should be at least twenty so that vacancy rather than divacancy motion is probably responsible for the annealing. The increase in annealing rate observed after quenches from above 750°C may result from dislocation motion produced by the force on the dislocation which arises from its presence in a vacancy concentration gradient.

* Partially supported by the Office of Ordnance Research.

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FRIDAY EVENING AT 7:00

Crystal Ballroom, Benjamin Franklin Hotel

(H. D. SMYTH presiding)

***Banquet of the American Physical Society***

After-dinner speakers: G. P. HARNWELL, T. G. FOX, G. HERZBERG, CYRIL S. SMITH

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SATURDAY MORNING AT 9:30

Irvine Auditorium

(N. BLOEMBERGEN presiding)

***DSSP Symposium on Double Magnetic Resonance***

**S1. Determination of Hyperfine Interactions in Solids by the Electron-Spin Double-Resonance Technique.** G. FEHER, *Bell Telephone Laboratories.* (35 min.)

**S2. Double Nuclear Magnetic Resonance and Dipolar Interaction in Solids.** R. M. COTTS, *Stanford University.* (30 min.)

**S3. Acoustically Induced Transitions between Nuclear Spin Levels.** W. H. TANTTILA, *Michigan State University.* (30 min.)

**S4. The Design and Performance of a C.W. Solid-State Maser.** D. SCOVIL, *Bell Telephone Laboratories.* (30 min.)

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SATURDAY MORNING AT 9:30

Physical Sciences, Room A-2

(W. KOHN presiding)

***Invited Paper***

**T1. Lattice Vibrations in Diamond-Type Crystals.** F. HERMAN, *RCA Laboratories.* (30 min.)

***Solid-State Theory***

**T2. Short Wavelength Cutoff for Plasma Oscillations of a Degenerate Electron Gas.*** RICHARD A. FERRELL, *University of Maryland.*—Previous work[1] has been extended to determine the shortest wavelength at which plasma oscillations can be sustained. The maximum wave number corresponds to the momentum just sufficient to cause an electron at the surface of the Fermi sea to make a real transition, absorbing one plasma quantum of energy. Applying this criterion to the Bohm-Pines[2] dispersion relation results in the following relation between $r_s$, the unit sphere radius, and $\beta$, the cut-off ratio: $r_s=6.02\beta^2 \times[(2+\beta)\ln(1+2/\beta)-2]^{-1}$. For aluminum ($r_s=2.07$) this yields $\beta=0.74$, and the maximum angle for inelastic scattering of 25 kev electrons is 16 m radians, in agreement with Watanabe's[3] measurement of 15–18 m radians.

* Investigation supported by the Office of Naval Research.

[1] R. A. Ferrell, Phys. Rev. **101**, 554 (1956).
[2] D. Bohm and D. Pines, Phys. Rev. **92**, 609 (1953).
[3] H. Watanabe, J. Phys. Soc. Japan **11**, 112 (1956).

**T3. Maxwell-Boltzmann Equation for Coulomb Interactions.** A. B. BHATIA, *University of Alberta,* AND G. E. TAUBER, *Western Reserve University.**—In problems involving electrical discharges or scattering of electrons by lattice vibrations it has been customary to neglect the Coulomb interaction between electrons. It has been shown by Landau[1] that those inter-

actions can be taken into account quite easily, because, on account of the long range character of the Coulomb forces, only a small momentum exchange takes place. Landau's results are rederived from first principles and the integro-differential equations for the distribution function obtained for Maxwell-Boltzmann and Fermi-Dirac statistics. The results are applied to the electron-electron interaction in gas discharges. If the electron-lattice interaction in metals (or semiconductors) can be characterized by a relaxation time, the transport equations including electron-electron collisions can be obtained in a similar fashion and solved in special cases, which enables one to calculate the modified expressions for the electric and thermal current densities.

* Part of this work was carried out for the Solid State Physics Division of the Franklin Institute.
[1] L. Landau, Physik. Z. Sowjetunion **10**, 154 (1936).

**T4. Optical Phonon Contribution to Cascade Capture.*** M. Lax, *Bell Telephone Laboratories.*—The resistivity of a crystal is only moderately increased, at temperatures below the Debye temperature by scattering due to optical phonons (or high-energy acoustic phonons, and intervalley scattering) because (1) there are few such high-energy phonons to be absorbed and (2) there are few electrons with enough energy to emit such phonons. In the neighborhood of a trap, however, the speedup of the electron is quite important. In the case of Coulomb attraction, the electron can acquire an energy $\hbar\omega$ by coming within the distance $(e^2/K\hbar\omega)$, and collisions with optical phonons become likely ($K$=dielectric constant). Such collisions are important for trapping since they lead to binding energies $>kT$, and hence a high probability of sticking. At room temperature, in silicon, this seems to be the dominant mechanism. At lower temperatures, the previously proposed* mechanism involving the usual acoustic phonons will predominate, since it is only necessary for the electron to gain enough energy to lose several $kT$, and the radius at which this occurs will be $\gg(e^2/K\hbar\omega)$ at low enough temperatures. In any case, progress to the trap ground state is made by a succession of one-phonon processes, rather than a single multiphonon jump.

* M. Lax, Bull. Am. Phys. Soc. Ser. II, **1**, 128 (1956).

**T5. Physical Concepts of the Polaron.** Jordan J. Markham, *Zenith Radio Corporation.*—Recent treatments of the polaron have emphasized means of solving a Hamiltonian due to Frohlich, rather than the physical concepts involved. This is an attempt to develop the physics of the problem. Several limitations inherent in the Hamiltonian will be indicated and discussed. The author will show why it cannot be split into three parts: one associated with the phonon field, the other with the electron, and the third representing the interaction. This is done in nonpolar solids and quantum electrodynamics. Finally, the relation between the recent approaches and the one made by Seitz and the author will be considered.

**T6. On Electronic Current of NiO.*** Jiro Yamashita,† *University of Pittsburgh.*—We shall discuss conduction mechanism by motion of an extra-electron which is tightly bound to an ion in an ionic lattice. We assume that the wave function of the electron is localized closely around an ion and motion of the electron is so slow that the lattice polarization is induced around the electron. In this case conduction mechanism may not be well explained by the usual band theory, but it might be better to use the Heitler-London picture and to understand the current as a result of wandering motion of the electron from ion to ion.

* This research was supported by the U. S. Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command.
† On leave from the Institute of Science and Technology, University of Tokyo, Tokyo, Japan.

**T7. Relationship between Wannier Functions and the Method of Strong Binding.*** John B. Gibson, *Brookhaven National Laboratory.*—The strong binding method to determine electronic wave functions[1] in solids consists of using orthonormalized atomic functions as approximate Wannier functions. These are combined into approximate wave functions as follows (for the $p$th band): $b_p^0(\mathbf{r},\mathbf{k})=N^{-\frac{1}{2}}\sum(\mathbf{R}_n)\times\exp(i\mathbf{k}\cdot\mathbf{R}_n)a_p^0(\mathbf{r}-\mathbf{R}_n)$. The $\mathbf{R}_n$'s are lattice points. $N$ is the number of atoms in the crystal. The approximate wave functions are then combined to form the exact wave function as follows: $b_q(\mathbf{r},\mathbf{k})=\sum(p)s_{pq}(\mathbf{k})b_p^0(\mathbf{r},\mathbf{k})$. A theorem of Slater's[2] can be used to show that the coefficient $S_{pq}(\mathbf{R}_n)$ in the expansion of the exact Wannier function in terms of the approximate Wannier functions, $a_q(\mathbf{r})=\sum(\mathbf{R}_n,p)S_{pq}(\mathbf{R}_n)a_p^0(\mathbf{r}-\mathbf{R}_n)$, is given by the Fourier transform of $s_{pq}(\mathbf{k})$, that is, $S_{pq}(\mathbf{R}_n)=\Delta^{-1}\int s_{pq}(\mathbf{k})\exp(i\mathbf{k}\cdot\mathbf{R}_n)d\mathbf{k}$. The integration is over the volume of the Brillouin zone $\Delta$. In general, $s_{pq}(\mathbf{k})$ for degenerate bands is rapidly varying in $\mathbf{k}$, consequently $S_{pq}(\mathbf{R}_n)$ falls off slowly in $\mathbf{R}_n$. Thus for these cases the Wannier functions are poorly localized. A nondegenerate band probably has a well-localized Wannier function since $s_{pq}(\mathbf{k})$ usually varys slowly with $\mathbf{k}$.

* Under the auspices of the U. S. Atomic Energy Commission.
[1] J. C. Slater and G. F. Koster, Phys. Rev. **94**, 1498 (1954).
[2] J. C. Slater, Phys. Rev. **87**, 807 (1952).

**T8. Band Structure of Tellurium and Selenium.** R. H. Asendorf, *Westinghouse Research Laboratories.*—A group theoretical analysis of the space group and Brillouin zone of tellurium and selenium has been made.[1] The proper linear combinations of atomic wave functions are obtained and a tight-binding calculation is set up for an explicit determination of the band structure. For simplicity, only $p$ functions are used. First and second nearest-neighbor interactions are taken into account using the two center approximation. Contributions of the first and second nearest neighbors are estimated using Slater's atomic orbitals and the work of Roothaan.[2] The energy *vs* wave-vector curves are discussed along the line of highest symmetry in the Brillouin zone. Comparison is made with the work of Reitz.[3]

[1] R. H. Asendorf, J. Chem. Phys. (to be published).
[2] C. C. J. Roothaan, J. Chem. Phys. **19**, 1445 (1951).
[3] John R. Reitz, Bull. Am. Phys. Soc. Ser. II, **1**, 331 (1956).

**T9. Band Structure of Thorium.*** Guy W. Lehman, *Atomics International.*—The energy band structure for the lowest conduction band in f.c.c. thorium has been completed. The ten $6d$ atomic orbitals appropriate for spin-orbit coupling are basic functions for these bands. $6d_{\frac{1}{2}}-6d_{\frac{5}{2}}$ atomic level separation is taken as 0.4 ev (Fermi-Thomas calculation). The energy matrix elements, neglecting spin-orbit coupling, are almost proportional to those derived from Slater-Koster LCAO method for the $3d$ band of f.c.c. nickel except that $(dd\sigma)$, $(dd\pi)$, and $(dd\delta)$ are equal to $-0.254\ E_0$, $0.131\ E_0$, and $-0.024\ E_0$ where $E_0$ is a parameter chosen to fit low temperature $C_p$ data. The energy levels obtained from diagonalizing the $10\times10$ matrix at 150 points in the $BZ$ were doubly degenerate. All accidental degeneracies along (001), (011), and (111) directions were removed by spin-orbit coupling. Only two overlapping bands are important in conduction processes in thorium. Multiple ellipsoidal Fermi surfaces lie along (001), (011), and (111). Effective number of holes and electrons were 0.1/atom with an average Fermi energy of 0.2 ev. Effective mass ratios range from $-2$ to $+2$ with cubic anisotropy present. Density of states near the Fermi level was computed. Correlation with Hall, magnetoresistivity, and thermoelectric power data will be given.

* This work was supported by the U. S. Atomic Energy Commission.

**T10. Vibrations of Small Crystals.*** Harvey Kaplan, *University of Buffalo.*—The vibrational modes of small, regular,

one-, two-, and three-dimensional monatomic arrays with free boundaries have been investigated. One major point of interest is the existence of surface, edge and corner modes which decay approximately exponentially towards the bulk of the material. Most of the cases investigated thus far use the model of nearest neighbor forces (both central and noncentral) only. For such a model surface waves exist only if springs differing from those in the bulk of the material are introduced at the surface. If the surface springs are stronger than the volume springs, some of the surface modes have frequencies outside of the volume mode band. The model is perhaps useful in discussing the vibrational properties of materials such as carbons of low heat treatment temperatures. These materials consist of largely randomly arranged graphite platelets, with diameters as small as 30 A, joined by a small number of bonds. The specific heat of such a substance has been computed assuming that the intercrystalline bonds serve only to establish thermal contact between adjacent crystallites and do not otherwise affect the vibrational spectrum. The effect of intercrystalline bonding on the vibrational modes will, however, also be discussed.

* Supported in part by the U. S. Atomic Energy Commission.

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SATURDAY MORNING AT 9:00

Houston Hall Auditorium

(G. HERZBERG presiding)

## *Chemical Physics*

## *Symposium of the DCP on High-Temperature Vaporization*

**U1. Indirect Methods for Establishing Vapor Species in High-Temperature Vaporization.** P. A. GILLES, *University of Kansas.* (30 min.)

**U2. Molecular Dissociation-Energies from Thermodynamic Equilibria Studied with a Mass-Spectrometer.** W. A. CHUPKA, *Argonne National Laboratory.* (30 min.)

**U3. The Use of Optical Spectroscopy for Studies of High-Temperature Vaporization.** J. L. MARGRAVE, *University of Wisconsin.* (30 min.)

**U4. Evaporation Processes with Activation Energies Larger than the Energies of Evaporation.** A. W. SEARCY, *University of California.* (30 min.)

## *Business Meeting of the Division of Chemical Physics*

(To be held during Session U whenever Chairman desires.)

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SATURDAY MORNING AT 9:00

Physical Sciences, Room A-1

(T. G. FOX presiding)

## *High-Polymer Physics, V*

## *Invited Paper*

**V1. Molecular Theories of Flow of Molten Polymers.** Y. H. PAO, *E. I. duPont de Nemours and Company.* (40 min.)

## *Contributed Papers*

**V2. Photoelastic Properties of Polystyrene in the Glassy State. I. Effect of Molecular Orientation.** R. D. ANDREWS AND J. F. RUDD, *The Dow Chemical Company.*—The effect of molecular orientation on the stress-optical coefficient of polystyrene at room temperature was measured using polystyrene monofilaments with different degrees of orientation. High degrees of orientation were obtained by cold-stretching. The optical measurements were made using a polarizing microscope fitted with a Sénarmont compensator. The stress-optical coefficient shows a strong dependence on molecular orientation, using birefringence as the index of molecular orientation. The stress-optical coefficient appears to decrease linearly *vs* birefringence, from a value of about +10 brewsters at zero birefringence to a value of about +4 brewsters at −0.04 birefringence. The elastic (Young's) modulus was also measured (in tension) as a function of orientation, and was found to increase nonlinearly with orientation (from $4.3\times10^5$ psi at zero birefringence to $6.1\times10^5$ psi at −0.04). A curve of strain-optical coefficient *vs* orientation was obtained by multiplying stress-optical and modulus values; this decreases nonlinearly and to a somewhat lesser extent than the stress-optical curve (from about +0.03 at zero birefringence to +0.017 at −0.04).

**V3. Photoelastic Properties of Polystyrene in the Glassy State. II. Effect of Temperature.** J. F. RUDD AND E. F. GURNEE, *The Dow Chemical Company.*—The effect of temperature on the stress-optical coefficient of polystyrene was measured at twelve different temperatures from +24° to −195°C using samples of unoriented polystyrene sheet. The stress-optical coefficient appears to decrease with temperature from a value of about +17 brewsters at −195°C to a value of about +10 brewsters at room temperature. The

elastic (Young's) modulus was also measured as a function of temperature using a flexural technique and was found to decrease linearly with temperature (from $6.36\times10^5$ psi at $-198°$ to $4.65\times10^5$ psi at $+24°C$). A curve of strain-optical coefficient *vs* temperature was obtained by multiplying stress-optical and modulus values; this increases nonlinearly with decreasing temperature. A theoretical calculation of the stress-optical coefficient at absolute zero is also presented and a comparison is made between the calculated result and the value obtained by extrapolation of the experimental data.

**V4. The Turbidity of Polyethylene.*** S. BUCKSER, R. S. STEIN, AND F. A. BETTELHEIM, *University of Massachusetts.*—The transmission of light by a nonabsorbing polymer film serves to characterize its light scattering properties. The wavelength dependency of scattering serves as a measure of the particle size of the scattering entity. For polyethylene, the Rayleigh—Debye-Bueche theory is inadequate and the more exact Mie theory of scattering must be employed. The variation of turbidity with temperature, cooling rate, stretching, and swelling have been studied. The turbidity (and wavelength dependency) exhibit a heating-cooling hysteresis similar to that observed by direct scattering measurement. Quenching results in less scattering and a smaller apparent particle size than does slow cooling. Stretching samples results in a decrease in turbidity but an increase in apparent particle size (indicating a decrease in the refractive index difference between the scattering particle and its surroundings). The change in turbidity and apparent particle size occurring upon swelling with solvents of differing refractive index is comparatively small. This observation is also confirmed by measurement of the angular dependency of scattering from swollen samples.

* Supported in part by a contract from the Office of Naval Research.

**V5. The Birefringence of Polyethylene Films.*** F. A. BETTELHEIM AND R. S. STEIN, *University of Massachusetts.*—The birefringence of stretched polyethylene results principally from (1) orientation birefringence of anisotropic crystals, (2) orientation of anisotropic amorphous chains, and (3) form birefringence due to anisotropically shaped objects being imbedded in a medium of different refractive index. Contribution (1) may be investigated by establishing crystal orientation by x-ray diffraction. The form birefringence contribution may be studied by measuring the birefringence of stretched polymers swollen with solvents of differing refractive index. The results of such a study are interpreted in terms of Wiener's theory of form birefringence of rods. The results are consistent with a model in which a rod-shaped aggregate of crystals orients in the stretching direction. The orientation of the rods is higher than that of the crystals themselves. The environment of these rods is a mixture of other rods and swollen amorphous polymer. The rods could be interpreted in terms of the helical aggregates of crystals proposed by Keller and Morgan, or the conical aggregates proposed by Bryant.

* Supported in part by a contract from the Office of Naval Research.

**V6. Dityndallism and Bidissymetry and Their Prospective Usefulness in Colloid and Polymer Research.*** WILFRIED HELLER, *Wayne State University.*—The effect of dityndallism discovered and quantitatively studied first on colloidal solutions of inorganic materials, is defined by $(i_{\parallel}-i_{\perp})_{\gamma}$ where $i_{\parallel}$ and $i_{\perp}$ are a measure of the total light intensities scattered, at an angle $\gamma$ relative to the incident linearly polarized beam, if its electric vector vibrates parallel and perpendicular, respectively, to the extraordinary direction of the dispersed system or solution subjected to the orienting effect of an external field or internal shear gradient. Since the effect has been proven to be very sensitive to the shape of light scattering material, it provides a powerful tool for obtaining quantitative information on the shapes of rigid colloidal particles and macromolecules and on the statistical shape of flexible macromolecules. The principal features of the effect and an experimental approach to its study will be described. If the incident beam is unpolarized, the shape of the scattering material affects the contours of the radiation envelope differently in a plane containing and the plane perpendicular to the extraordinary direction, resulting for dimensions which are not small compared to the wavelength in a twofold dissymetry. The cause of this effect, to be termed "bidissymetry," and an experimental approach to its measurement will be discussed.

* This work was supported by the Office of Naval Research and the Office of Ordnance Research.

**V7. Theory of Flow Bidissymetry of Light Scattering by Flexible Macromolecules.*** ANTON PETERLIN, WILFRIED HELLER, AND MASAYUKI NAKAGAKI, *Wayne State University.*—A theoretical equation to give the intensity of light scattered by a solution of flexible macromolecules oriented in laminary flow is derived. The principal variables considered are the direction of observation, the shear gradient, and the mean square end-to-end distance. The optical part of the theory makes use of the well-known interference treatment of light scattering by Debye. In the hydrodynamic part of the theory, the present first approach considers the polymer molecule as a freely draining coil neglecting the hydrodynamic interaction. The theory shows that the probability distribution of the segments has, at finite shear gradients, the symmetry of an ellipsoid whose major axis forms an angle $\chi$ with the direction of the velocity gradient. Both the angle $\chi$ and the axial ratio of the ellipsoid increase with increasing shear gradient. The intensity of scattered light was calculated on the basis of the equation arrived at for the following variables: (1) magnitude of the shear gradient; (2) magnitude of the mean square end-to-end distance; (3) angles of observation varying between 60° and 120°, both in a plane containing and in a plane perpendicular to the direction of flow. The intensity of scattered light was found to vary appreciably with all the variables considered.

* This work was supported by the Office of Ordnance Research.

**V8. Theory of Flow Dityndallism of Flexible Macromolecules.*** MASAYUKI NAKAGAKI AND WILFRIED HELLER, *Wayne State University.*—The dityndallism and the related depolarization of light scattered by flowing polymer molecules is calculated assuming that (1) the molecule subjected to a shear gradient is a statistical spheroid (see preceding abstract) (2) the spheroid density is uniform, and (3) its refractive index is the mean of the refractive index of the polymer and of the solvent contained in the spheroid. The hydrodynamic part of the theory outlined in the preceding abstract and the theory of scattering by spheroids developed by A. F. Stevenson in connection with a related project, were incorporated in the present theory. Dityndallism and depolarization were calculated as functions of shear gradient and for various effective relative refractive indexes. The differential radiation envelope in the plane perpendicular to the direction of flow was considered from 0°–180°. The radiation in the plane perpendicular to the incident beam (which is assumed to be perpendicular to the direction of flow) was considered for 60°, 90°, and 120°. Dityndallism and depolarization to be expected in the former plane proved to be more promising theoretically. Numerical results, calculated on the basis of the present theory, lead to the expectation that the mean square end-to-end distance of flexible macromolecules, both at rest and upon deformation during flow, can be obtained.

* This work was supported by the Office of Ordnance Research.

**V9. Correlation of Normal Stresses with Other Properties of Polymer Solutions.** WLADIMIR PHILIPPOFF, *Franklin Institute Laboratories.*—In previous communications[1] the connection between normal stresses, flow birefringence, and flow

curves has been investigated on polyisobutylene solutions in decalin. It was found that "Hooke's law" in shear was valid for a large range of variables. The same measurements have now been extended to solutions of nitrocellulose in butyl acetate. It was found that the same correlation exists. However, Hooke's law in shear is not valid. This suggests a parallelism of stress-strain-and optical tensors in flowing solutions of high polymers. These results confirm the idea of Weissenberg that in flowing solutions of high polymers, a condition of elastic stress is present. The parallelism is not dependent on the stress and strain tensors being proportional to each other (nonlinear stress-strain law).

[1] Nature **178**, 811–812 (1956) and W. Philippoff, J. Appl. Phys. **27**, 984–989 (1956).

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SATURDAY MORNING AT 9:30

Museum Auditorium

(R. SMOLUCHOWSKI presiding)

## *Irradiation Effects; Metals and Insulators*

**VA1. Formation of Color Centers in Alkali Halides as Function of Energy of Incident Protons.*** E. PEARLSTEIN, K. KOBAYASHI, AND B. MOZER, *Carnegie Institute of Technology.*—The concentration of *F*-centers produced in NaCl and KCl during an irradiation with protons of energies between 90 and 400 Mev was determined. Growth curves of *F*-center concentration were measured in order to distinguish between *F* centers associated with negative ion vacancies newly formed by protons and those associated with vacancies present before irradiation. This permitted an evaluation of the number of *F* centers produced per proton per centimeter path $\alpha$. A plot of $\alpha$ *vs* reciprocal energy of protons is an almost straight line for NaCl, and it bends slightly upwards for KCl. These results are compared with the stopping powers of the crystals for protons of these energies, and are found to be in good agreement with each other. This indicates that ionization is the dominant factor in producing color centers in these crystals by proton irradiation.

* This work has been supported by the U. S. Atomic Energy Commission.

**VA2. Density Change of Sodium Chloride Produced by Proton Irradiation and Its Thermal Annealing.*** KOICHI KOBAYASHI, *Carnegie Institute of Technology.*—The changes of the density of sodium chloride crystals produced by irradiation with 350-Mev protons and the recovery process during annealing at several temperatures were studied. The measurements of the density changes were made by means of the observation of a difference in the flotation temperatures between irradiated and nonirradiated crystals in a liquid. The volume changes per unit volume of NaCl were measured as $3.0_1\times10^{-4}$ and $2.7_5\times10^{-4}$ for the crystal after irradiation with a total flux of $8.1\times10^{15}$ and $7.1\times10^{15}$ protons per cm$^2$, respectively. The number of vacancies was estimated from the volume expansion and was found to be in fairly good agreement with that estimated from the previous stored energy data.[1] The recovery of the volume changes with thermal annealing was studied as a function of temperature rising at a rate of 2°C/min. The results show that the density change of an irradiated crystal remains constant up to about 200°C and then drops sharply to about one half of its original value between 200–230°C. Above this temperature the density increases linearly with temperature and returns to that of a normal crystal at 400°C. These changes were found to be related closely to the behavior of *F*, *V*, and coagulation centers[1] and will be discussed from this point of view.

* This work has been supported by the U. S. Atomic Energy Commission.
[1] K. Kobayashi, Phys. Rev. **102**, 348 (1956).

**VA3. Reactor and Gamma-Ray Induced Coloring of Corning Fused Silica.*** PAUL W. LEVY, *Brookhaven National Laboratory.*—We have irradiated, under various conditions, many different samples of fused and crystalline quartz. All of these develop absorption bands in the region 0.2 to 1 micron. Since the bands overlap and are broad, resolution of the observed spectrum into component absorption bands is difficult. Corning fused silica is colored less than all other silica samples and its spectrum is the most susceptible to a detailed resolution into component bands. When irradiated at 70°C there is one strong band at 218 m$\mu$ and a small one at approximately 242 m$\mu$.[1] However, after irradiating this material in the reactor at liquid nitrogen temperature the 242 m$\mu$ band is almost as intense as the 218 m$\mu$ band. When a sample originally colored in the reactor is subsequently subjected to gamma rays additional absorption bands appear. The intensity of the latter bands increase in proportion to both the reactor and gamma-ray exposure. Also, by thermal bleaching of irradiated samples the presence of another band is indicated. In all, at least four new absorption bands in this material is indicated.

* Work performed under auspices of the U. S. Atomic Energy Commission.
[1] Paul W. Levy, J. Chem. Phys. **23**, 764 (1955).

**VA4. Transmission Limits and Irradiation of High-Purity Fused Silica.** H. B. KLEVENS, *Mellon Institute.*—Samples of high-purity fused silica, obtained from Corning Glass Company, were found to fall into two groups. One group (*A–D*) had transmission limits of 1580–1640 A; the other (*E–F*) of 1720 A. From previous studies on similar silica as well as a number of synthetic quartz preparations, it was assumed that these differences were due to varying concentrations of $H_2O$ or rather $-$OH in the samples. However, group *A–D* showed absorbance values at 3668 cm$^{-1}$ (2.72 $\mu$) of 1.34–1.39; group *E–F* of 1.37–1.38, all for equal thicknesses. Careful spectrographic analysis showed no impurity differences in these two groups. Upon irradiation (to saturation of a color center at 2140 A), the transmission limits of both groups were identical at 1730 A. Irradiation,[1] with a 2-Mev Van de Graaff accelerator (High Voltage Engineering), resulted in equal saturation values, 5.2 cm$^{-1}$ at 2140 A, for both groups. However, samples *E–F* colored much more rapidly than *A–D*. Si$^{29}$ relaxation times were about 10 hours for samples *A–D* and only about 1.5 hours for *E–F*.[2] High-temperature baking of these samples, coupled with some of the above measurements, may throw more light on these various differences.

[1] Irradiations were kindly done by Dr. A. Stonehill, Ethicon, Inc.
[2] Holzman, Anderson, and Koth (unpublished data).

**VA5. Effect of X-Rays on the uv Spectrum of Fused Germania.** ALVIN J. COHEN AND HERBERT L. SMITH, *Mellon Institute.*—Fused germania ($GeO_2$) contains an intense absorption band centered at 2445 A caused by a reduced germanium species probably Ge(II).[1] This band has the same

half-width as a band centered at 2429 A in fused silica and produced by the same germanium species contained as an impurity.[2] Upon x-irradiation of the germania a color center is produced below 2200 A. This color center gradually smothers the 2445 A band which is slowly bleached during x-ray treatment. A color center specific to germanium-doped synthetic quartz with maximum in the 270–280 mμ region will be discussed.

[1] A. J. Cohen, Phys. Rev. (to be published).
[2] V. Garino-Canina, Compt. rend. **242**, 1982 (1956).

**VA6. Displaced Atom Concentration in $\alpha$-$Al_2O_3$ as Determined by Neutron Scattering.** J. J. Antal, *Materials Research Laboratory, OMRO,* and G. J. Dienes, *Brookhaven National Laboratory.**—The concentration of point defects in aluminum oxide produced by pile irradiation has been determined by a long wavelength transmission experiment. The concentration as a function of fast neutron bombarding flux is in agreement with hydrostatic density changes (assuming the defect volume equals the atomic volume) measured on the same samples. There is also agreement with optical transmission data for lower irradiations.[1] Calculations according to Kinchin and Pease[2] indicate a concentration some 30 times greater. Annealing at the temperature of irradiation (<40°C) is probably the explanation for the low concentration observed.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] Paul W. Levy and G. J. Dienes, *Bristol Conference on Defects in Crystalline Solids* (The Physical Society, London, 1955).
[2] G. H. Kinchin and R. S. Pease, Repts. Progr. in Phys. **XVIII**, 1 (1955).

**VA7. Low-Temperature Annealing Process in Irradiated Metals. Part A. Effect of Defect Concentrations in Copper.** C. E. Klabunde, T. H. Blewitt, R. R. Coltman, and T. S. Noggle, *Oak Ridge National Laboratory.**—The discovery that the radiation induced electrical resistivity of copper anneals at 30–50°K led to the early suggestion that interstitial atoms are mobile in this temperature range and are annihilated by vacant lattice sites. If close pair annihilation is excluded, an annealing process of this type should have a unique activation energy and be of second order. Recent experimentation on copper has shown that this is not the case. The isothermal annealing curves obtained at 45°K following a bombardment at 18°K of $1\times10^{16}$ neutrons/cm$^2$ in the hole No. 12 cryostat of the ORNL Graphite Reactor was compared with that obtained after $5\times10^{17}$ neutrons/cm$^2$ and it was found that these curves when normalized were identical within experimental error. These data show that the annealing proceeds by a first-order process and this coupled with the nonexponential shape of the isothermal annealing curves implies that the activation energy is not unique. It can then be concluded that the low-temperature annealing process in neutron-irradiated metals and in particular copper is not the result of the migration of interstitial atoms to vacant lattice sites. This conclusion is in accord with that deduced earlier from stored energy measurements.

* Supported by the U. S. Atomic Energy Commission.

**VA8. Low-Temperature Annealing of Irradiated Metals. Part B. Effect of Sample History.** T. S. Noggle, T. H. Blewitt, R. R. Coltman, and C. E. Klabunde, *Oak Ridge National Laboratory.**—The annealing of metals irradiated in the hole No. 12 cryostat in the Oak Ridge Graphite Reactor has been studied by a pulse annealing technique over the temperature range of 20–300°K. Both isochronal and isothermal techniques have been employed in studying the annealing of metals bombarded at 15–20°K. Isothermal annealing studies show that the annealing process occurring in the 35–50°K interval cannot be accounted for by simple reaction rate theory assuming a unique activation energy and a low order for the process. Experiments show that the annealing is unaffected by the dislocation structure or by prior room temperature irradiation. This indicates that the annealing observed is not associated with migration of radiation induced defects to dislocations or to the defects left after room temperature irradiation. Dislocations may however play a role in the annealing at higher temperatures as the isochronal annealing seems to be dependent on dislocation density. Impurity atoms may play an important role in the very low temperature annealing as this process is suppressed in $\alpha$-brass.

* Supported by the U. S. Atomic Energy Commission.

**VA9. Effect of Neutron Irradiation on Twinning in Copper.** T. H. Blewitt and J. K. Redman, *Oak Ridge National Laboratory.**—It has been previously reported[1] that copper single crystals when deformed at 4.2°K will elongate by the normal slip process when the shear strain is small. As the elongation increases, an anomalous flow process called discontinuous slip becomes operative and at still larger strains the flow process changes to mechanical twinning. Experiments show that heavy neutron bombardment ($7\times10^{20}$ nvt) can raise the flow stress sufficiently so that the normal glide process is completely suppressed at 4.2°K and the sample immediately flows by discontinuous slip. This slip is localized and spreads through the sample as a widening band sometimes called a Luder's band. After the band has grown to a sufficient size, a mechanical twin lamella forms in this Luder's band stopping the discontinuous slip, the sample elongating entirely as a result of twin formation. The twin lamella grows until it has completely filled the Luder band at which point the twin formation ceases and the sample fractures. It is possible to deduce that the discontinuous slip is the result of a packet of about $10^8$ dislocations moving to the surface to form about 30 slip lines.

* Supported by the U. S. Atomic Energy Commission.
[1] Blewitt, Redman, Sherrill, and Coltman, Phys. Rev. **98**, 1555(A) (1955).

**VA10. X-Ray Study of Deuteron Irradiated Copper at 12°K.*** R. O. Simmons and R. W. Balluffi, *University of Illinois.*—The lattice expansion of an irradiated high-purity copper single crystal foil was measured at 12°K under conditions analogous to those of an earlier electrical resistivity experiment.[1] The expansion was proportional to the integrated flux of incident 12-Mev deuterons within measurement error (about $1\times10^{-5}$). For a flux of $6.3\times10^{16}$ deuterons/cm$^2$ the expansion was $\Delta d/d = 2.6\times10^{-4}$ at the foil back surface where the deuteron energy was 7 Mev. Diffractometer measurements at 12°K showed very small line broadening due to irradiation (increase of line width at half-maximum <20%). Previous thermal expansion measurements[2] permitted a study of the annealing of the radiation-induced expansion during subsequent warming. In the narrow temperature range 15–42°K about 55% of the effect annealed out. Between 42 and 227°K a further 20% disappeared and annealing was completed at 302°K. The apparent very slight line broadening also disappeared after warming to 227°K. The results appear consistent with the production of a concentration $c$ of Frenkel defects about 1/14 that predicted by the simple theory of displacements, assuming $(\Delta d/d)\simeq c$.

* Work supported by the U. S. Atomic Energy Commission.
[1] Cooper, Koehler, and Marx, Phys. Rev. **97**, 599 (1955).
[2] R. W. Balluffi and R. O. Simmons, Bull. Am. Phys. Soc. Ser. II, **2**, 137 (1957).

**VA11. Retardation of Zone Growth in an Al-Ag Precipitate Alloy by Previous Fast Neutron Irradiation.** R. E. Jamison, *Oak Ridge National Laboratory.*—Al–20 wt % Ag foils, quenched from 520°C, were given various times at 20, 100, and 150°C, then irradiated by $10^{19}$ fast neutrons per cm$^2$ at about 40°C. Following irradiation, small angle x-ray scattering values were determined as a function of time at various tem-

peratures (100, 130, 165°C). The irradiation causes the plot of predominate zone size *vs* time at temperature to diverge downward from the normal, e.g., 20 hours at 100°C for a previously irradiated sample with zone radius of gyration equal to 13.3 A is roughly equivalent to 5 hours at 100°C for an originally identical unirradiated sample. Arbitrarily defining retardation as the difference between the time at temperature for the irradiated specimen, and the time at temperature for the unirradiated specimen, to produce the same zone size in each, we see that it increases to a maximum with increasing time at temperature and then decreases, eventually returning to the value of zero. For any particular zone size, the retardation decreases with increasing temperature and decreases with increasing initial zone size.

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SATURDAY AFTERNOON AT 1:30

Museum Auditorium

(H. B. CALLEN presiding)

## *DSSP Symposium on Theoretical Topics*

**W1. A Theory of the Properties of Liquid Helium 3 and Liquid Helium 4.** K. A. BRUECKNER, *University of Pennsylvania.* (30 min.)

**W2. Statistical Basis of the Boltzmann Equation.** J. ROSS, *Yale University.* (30 min.)

**W3. Theory of the Transport Equation in a Quantum-Mechanical System.** J. M. LUTTINGER, *University of Michigan.* (30 min.)

**W4. Applications of Scattering Theory to the Study of Transport Phenomena in Many-Particle Quantum-Mechanical Systems.** K. M. WATSON, *University of Wisconsin.* (30 min.)

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SATURDAY AFTERNOON AT 1:30

Houston Hall Auditorium

(H. Y. FAN presiding)

## *Invited Paper*

**X1. Temperature Dependence of the Relaxation-Time Tensor for *n*-Type Germanium.** C. GOLDBERG, *Westinghouse Research Laboratory.* (30 min.)

## *Transport Diffusion and Lifetimes of Carriers*

**X2. Effect of Traps on Current Carrier Transport in Semiconductors.** W. VAN ROOSBROECK, *Bell Telephone Laboratories.*—The ambipolar treatment previously given is extended to include the effect of traps. Simultaneous partial differential equations are given for the transport of mobile carriers and for the related variations in concentrations of trapped carriers. Applications to photoconductivity, the photomagnetoelectric effect, and drift of a pulse have been considered. Mass-action relationships provide a general basis for trapping effects and recombination. For the steady state, modified ambipolar diffusivities and drift velocities apply to the concentrations of mobile electrons and holes. The diffusivities are such that the general Shockley-Read small-signal electron and hole lifetimes are associated with the same diffusion length. If equal capture frequencies per electron and per hole (or equal free times) obtain, then the traps give recombination only, with a single small-signal lifetime. The general small-signal solution for the drift of an injected pulse includes an attenuated pulse of untrapped carriers which drifts with the ambipolar velocity and leads a distribution which exhibits a peak if sufficient multiple trapping has occurred. For no recombination, this peak ultimately drifts at a fraction of the ambipolar velocity equal to the fraction of time carriers are free, while the fraction of carriers trapped approaches the fraction of time carriers are trapped.

**X3. Solution of One-Carrier Current-Flow Problems in Solids, Including Diffusion.** MURRAY A. LAMPERT, *RCA Laboratories.*—The inclusion of diffusive currents in one-carrier injection problems involving space charge appears generally to preclude purely analytical solutions, except in the simplest case. The complete solutions are necessary, however, for study of the role of the contact in such problems. By utilizing a topological property of the current flow it is possible, through a combination of digital-computer and analytical techniques to obtain a complete solution to any such problem for a one-dimensional, semi-infinite crystal for which the analytical solution is available with neglect of diffusion. Assuming, as a boundary condition, that the free carrier density at an infinite distance from the injecting contact is equal to its thermal-equilibrium value, then the relevant topological property is the monotonic-decreasing character of the free carrier density as a function of distance from the contact. With the current given, and the free-carrier density at the potential minimum sought as an eigenvalue, this property facilitates programing so as to obtain a quick and accurate solution on a digital-computer of intermediate capacity and speed. Solutions are presented for a problem of semiconductor and insulator physics involving a fixed component of excess charge in the solid, previously discussed in the literature, neglecting diffusion.

**X4. Lifetimes from Dynamic Photoconductivity Quenching.** FRANK MATOSSI, *U. S. Naval Ordnance Laboratory.*—It is shown that lifetimes of conduction electrons and time constants of trap filling under the influence of infrared radiation superimposed on equilibrium photoconductivity may be obtained from the phenomenological parameters of dynamic quenching curves, i.e., from equilibrium and maximum value, slope at origin, and time at which maximum occurs. The theoretical approach is similar to a previous treatment[1] except for the introduction of time constants in recombination terms.

[1] F. Matossi, J. Electrochem. Soc. **103**, 662 (1956).

**X5. Lifetime of Minority Carriers in Single Silicon Crystals.** J. S. BLAKEMORE, *Honeywell Research Center* (introduced by A. Nussbaum).—Minority carrier lifetime has been studied in $p$-type and $n$-type doped single crystals of silicon, using the photoconductive decay method. This method can be very reliable and reproducible when uniform specimens free from trapping and photovoltaic effects are used, and when penetrating light is used to generate carriers uniformly in depth. To achieve the latter result, a silicon filter should be used with a thickness greater than that of the specimen. While lifetime in $n$-type silicon is insensitive to light intensity, in $p$-type silicon the electron lifetime increases rapidly with electron density. For a group of boron-doped crystals, the variation of lifetime with $\Delta n$ is found to be strongest for $\Delta n < 10^{13}$ cm$^{-3}$. At higher levels of modulation, the slope relating $\tau_n(1+\Delta n/p_0)$ to $(\Delta n/p_0)$ is smaller, indicating the action of recombination centers similar in form to those discussed by Bemski.[1] The centers which appear to dominate recombination at very low levels are less prominent in silicon which has been regrown several times.

[1] G. Bemski, Phys. Rev. **100**, 523 (1955).

**X6. Experimental Determination of Injected Carrier Recombination Rates at Dislocations in Semiconductors.** J. P. MCKELVEY, *Westinghouse Research Laboratories.*—The recombination probabilities associated with lineage boundaries in germanium have been determined by measuring the ratio of injected carrier concentrations on either side of such a boundary and comparing the results with previous theoretical calculations.[1] Knowing the linear density of dislocations in the lineage boundary, the recombination cross section for a single dislocation can be inferred. The measured cross sections correspond to cylindrical recombination areas of diameter 1.15 A for holes in $n$-type germanium and 2.5 A for electrons in $p$-type germanium. On the basis of recombination at dislocations alone, these results can be used to compute the expected bulk lifetime as a function of dislocation density, and it is concluded from these calculations that a significant part of carrier recombination in the usual melt-grown crystals takes place at dislocations.

[1] J. P. McKelvey and R. L. Longini, Phys. Rev. **99**, 1227 (1955).

**X7. Hot Carrier Effects in $p$-Type Ge.*** R. BRAY AND K. MENDELSON, *Purdue University.*—The hot carrier effect[1] has been investigated in detail for $p$-type Ge. For uncompensated samples, with $N_A$ from $3\times10^{13}$ to $4\times10^{15}$/cm$^3$ and $\mu_H$ (77°K, 3400 gauss) from 41 000 to 15 000 cm$^2$/v sec, we observe, at 77°K, gradual transition with increasing $E$, from ohmic conductivity, $\sigma_0$ to $\sigma\alpha E^{-0.5}$ region, characteristic of all samples. No distinctive $E^{-1}$ region is observed. The $E^{-0.5}$ dependence applies in range 700 v/cm $\leq E \leq 10^4$ v/cm for purest samples. The common $E^{-0.5}$ dependence at high fields implies disappearance of impurity scattering for sufficiently "hot" carriers. In this range, values of $\mu_{H\sigma E}/\sigma_0 = \mu_E\mu_H/\mu_0$, coincide ($\pm5\%$) for all samples, implying $(\mu_H/\mu_0)$ and $\mu_E$ are independent ($\pm5\%$) of $N_A$ in range indicated. For compensated samples ($N_D/N_A \sim 0.6$), with $N_A - N_D$ from $10^{15}$ to $5\times10^{15}$/cm$^3$, and $\mu_H$(77°K, 3400 gauss) from 9000 to 2000 cm$^2$/v sec, we observe at 77°K, $\sigma$ first increases with $E$, then decreases at higher $E$. The largest rise, for most impure sample, is 50%. Increase in both impurity mobility and majority carrier concentration may occur since acceptors are not exhausted. At 195°K, $\sigma$ decreases monotonically with $E$.

* Work partially supported by Signal Corps contract.

[1] E. J. Ryder, Phys. Rev. **90**, 766 (1953).

**X8. Internal Field Emission in Silicon $p$-$n$ Junctions.** A. G. CHYNOWETH AND K. G. MCKAY, *Bell Telephone Laboratories.*—Internal field emission is believed to occur in narrow $p$-$n$ junctions in silicon. This conclusion is based on the following observations: (i) as in wide juctions, the multiplication characteristic has a positive temperature coefficient whereas the reverse characteristic, unlike wide junctions, possesses a negative temperature coefficient; (ii) the forward and reverse currents are relatively insensitive to temperature; (iii) radiative transitions of energetic carriers in the high field region result in the emission of visible light, the pattern of which shows that the current flows more or less uniformly through the whole extent of the junction but that the array of fewer and more intense light spots characteristic of avalanche breakdown is absent; (iv) the noise associated with the onset of avalanche breakdown is absent. It is concluded that in these narrow junctions the junction space-charge field due to the built-in potential alone is sufficient to result in a rate of carrier generation much greater than that of the normal thermal processes. By assuming a reasonable form for the voltage dependence of the field-generated current it proves possible to account qualitatively for the complex forward-bias characteristics of these junctions. The reverse characteristics show the onset of multiplication of field emitted carriers at a reasonable threshold. Possible causes of the softness of the reverse characteristics are discussed.

**X9. Temperature Variation of Equilibrium Barrier Height of a $p$-$n$ Junction.** L. J. FIEGEL, *Illinois Institute of Technology,* AND J. R. MADIGAN, *Hoffman Electronics Corporation.*—The equilibrium barrier height of a $p$-$n$ junction rectifier was measured as a function of temperature from 77° to 373°K. The barrier height was determined by observing the saturation of the open circuit junction decay voltage with increasing forward bias.[1] The height of the barrier at a given temperature is equal to the original difference in Fermi levels in the isolated $n$ and $p$ regions of the diode. At low temperatures it should, therefore, approach the energy gap and should tend to zero at high temperatures as both regions approach intrinsic material. Measurements on silicon alloy junction diodes are in general agreement with this predicted behavior and because of the heavy doping of the emitter essentially describe the behavior of the Fermi level in the base region.

[1] B. R. Gossick, J. Appl. Phys. **26**, 1356 (1955).

**X10. Drift Mobility Measurements Using a Junction, Constriction, or Point Contact Collector.** MILTON GREEN, *Signal Corps Engineering Laboratories.*—In these Laboratories, measurements of drift mobility have been made by observing the time of transit $t$ of a pulse of charge carriers over the distance $x$ between the point of photoinjection and a passive "collector." The "collector" may be a reverse biased junction, a constriction in the cross-sectional area, or a point contact electrode. The arrival of the injected pulse at the collector results in an increase in the conductance of the specimen large compared to that due to the carrier injection of the bulk material. A signal is observed on the CRO taken from a load resistor in series with the samples. $t$ is plotted against $x$. The reciprocal slope of the curve gives carrier velocity at each point which when divided by the field strength $E(x)$ gives the corresponding mobility $\mu(x)$. A planar junction gives the best results because the flow lines are rectilinear and all charges move approximately the same distance. For a junction, electron mobility is determined by injection in the $p$ region and hole mobility from injection in the $n$ region.

SATURDAY AFTERNOON AT 1:30

Physical Sciences, Room A-2

(F. SEITZ presiding)

## *Alkali Halides; Luminescence*

**Y1. Prebreakdown Currents and Breakdown in Alkali-Halide Crystals.*** M. E. CASPARI AND H. YOSHIKAWA, *University of Pennsylvania.*—Prebreakdown dc currents in single crystals of NaCl, KCl, and KBr have been measured over a wide temperature range as a function of the applied field strength. The electric breakdown strength could not be easily correlated with the dc conductivity. The dependence of $\sigma$, the conductivity, on $E$, the applied field, was very sensitive to surface irregularities at the cathode, but ln $\sigma$ was found to be roughly proportional to $E^{\frac{1}{2}}$, especially if there was much high field emission from the cathode. This behavior is to be expected if the conductivity is governed by thermally activated charge carriers such as electronic space charges, which have been introduced into the crystal by high field emission. Such space charge will always enhance the field at the anode, and, hence, decrease the apparent breakdown strength. The equilibrium current is determined by a lower field strength which may be sensitive to the actual space charge distribution. Hence, the conductivity, calculated from the current and the applied field, may not be correlated with the breakdown field.

* This work was supported by a grant from the National Science Foundation.

**Y2. Effect of Imperfections on the dc Breakdown Strength of Alkali Halide Crystals.*** H. YOSHIKAWA AND M. E. CASPARI, *University of Pennsylvania.*—The effect of annealing, plastic deformation, and x-ray irradiation on the dc electric breakdown strength of KBr, KCl, and NaCl crystals has been investigated at room temperature. Although annealing apparently reduced the breakdown strength, this reduction was caused by surface irregularities arising from thermal etching. In KBr, after annealing above 500°C, these take the form of step-like ridges along the [100] directions on cleaved (100) surfaces. Polishing the cathode surfaces after annealing restores the value for unannealed crystals. The irregularities at the anode had little effect on the breakdown strength. Irregularities at the cathode probably lead to increased high field emission with subsequent field distortion and enhancement of the field at the anode. Plastic deformation up to 2% compression had little effect on the electric strength. X-ray irradiation produced a marked lowering of the breakdown strength unless the crystals were bleached after the irradiation. The breakdown strength of such bleached crystals was close to the value of nonirradiated samples.

* This work was supported by a grant from the National Science Foundation.

**Y3. Width of the *F* Band.** JOHN D. KONITZER AND JORDAN J. MARKHAM, *Zenith Radio Corporation.*—The work of Dorn and Haven suggests that there exists an absorption band associated with the $M$ under the $F$. We have measured the absorption in the $F$ region in KCl and KBr at 78°K and found that its structure is dependent on the presence of the $M$ and $R$ bands. The broadening in the presence of small amounts of $M$ absorption indicates that it is not simply due to the overlapping of $R$, $M$, and $N$ bands but is caused by an additional structure. These measurements support the present interpretation of the work of Dorn and Haven; they can explain the difference in the measurement of Pick and Geiger as well as the difference in the half-width observed by Mollwo and by Duerig and Markham.

**Y4. *F* Centers in X-Ray Irradiated KCl, NaCl, and Neutron-Irradiated LiF.*** F. J. REID, R. T. BATE, AND C. V. HEER, *Ohio State University.*—The number of magnetic centers in x-ray irradiated KCl, NaCl, and neutron-irradiated LiF were determined by measuring the static magnetic susceptibility down to liquid helium temperatures with a sensitive torsion balance. Optical absorption measurements were made at room temperature. Under the assumption that the temperature-dependent paramagnetic susceptibility is due primarily to the $F$ centers, optical oscillator strengths for KCl and NaCl were in agreement with previous results[1] on additively colored crystals. LiF crystals were irradiated with varying neutron fluxes, and the concentrations of magnetic centers exceeded $10^{20}$ per cubic centimeter in the intensely colored crystals. Concentration as a function of neutron flux will be discussed.

* This research was supported by the U. S. Air Force through the Office of Scientific Research of the Air Research and Development Command.

[1] C. J. Rauch and C. V. Heer, Phys. Rev. **105**, 914 (1957).

**Y5. Mechanical Effects of *F* Centers in KCl Crystals.*** TAIRA SUZUKI AND MASAO DOYAMA, *University of Illinois* (introduced by J. S. Koehler).—The present work aims to give a more detailed knowledge about mechanical effects of $F$ centers in KCl crystals introduced by additive coloration. It is found that critical shear stress does not change appreciably until the number of $F$ centers in crystal, $C_F$, reaches a certain value around $10^{16}$ cm$^{-3}$ depending upon the measuring temperature. The critical value of $C_F$ does not appear to depend on the vacancy concentration since quenching temperature does not alter $C_F^{crit}$. Critical shear stress increases in proportion to $(C_F)^{0.16}$ above $C_F^{crit}$. When crystals are brought to a temperature below room temperature immediately after quenching, critical shear stress is found to increase with time even at liquid nitrogen temperature. It is very remarkable that, when such crystals as aged for a certain time at the above temperature are brought quickly to room temperature and then held, the critical shear stress begins to fall to an equilibrium value at room temperature. This can be repeated by transferring crystals from one temperature to another. This is also true in crystals without $F$ centers, although the amount of hardening increases with $C_F$. The activation energy for the aging process determined from aging curves is very small, of order of 0.1 ev or less. No appreciable change in the $F$ band has been observed.

* Supported by the Office of Naval Research.

**Y6. Comments on *R* Center Production in Alkali Halides.** R. J. FRIAUF AND G. R. COLE,* *University of Kansas.*—It has recently been shown that the intensity ratio of $R_1$ to $R_2$ bands in colored KCl is nearly constant over a wide range of conditions, and theoretical calculations for the $F_2$ center have indicated that this center may well be responsible for *both* $R$ bands.[1] This viewpoint can be supported by consideration of the following phenomena. (1) The growth of $R$ and $M$ bands during illumination of a colored crystal with $F$ light[1,2] is consistent with the view that $F_2$ centers are formed from $M$ centers by the capture of an electron and the expulsion of a positive ion vacancy. (2) Our observation that the $M$ band increases whereas the $R$ bands decrease when a crystal is heated to 125°C appears to represent the inverse of the formation process. (3) We have also observed that the quantum

efficiencies for photoconductivity at room temperature are 0.9 and 0.5 (±25%) for the $R_1$ and $R_2$ bands, respectively, in accord with the idea that the $R_1$ band represents a transition to the higher energy level.

* Presently at Savannah River Laboratory, E. I. du Pont de Nemours Company.
[1] Herman, Wallis, and Wallis, Phys. Rev. **103**, 87 (1956).
[2] St. Petroff, Z. Physik **127**, 443 (1950).

**Y7. Hyperfine Structure Anisotropy in the Paramagnetic Resonance Absorption of *V* Centers in LiF.** TRUMAN O. WOODRUFF AND WERNER KÄNZIG, *General Electric Research Laboratory*.—The paramagnetic resonance absorption at −180°C of single crystals of KCl, NaCl, KBr, and LiF irradiated with x-rays at −180°C can be resolved into groups of $(4I+1)$ lines,[1] where $I$ is the spin of the halide nucleus. To explain the splittings within each group Castner and Känzig[1] include in the spin Hamiltonian terms of the form $a(\mathbf{I}\cdot\mathbf{S}) + bI_{z'}S_{z'}$. Here $z'$ refers to the axis of the molecule-ion paramagnetic center, which is tentatively identified with the $V_1$ optical absorption center. Using perturbation theory they deduce from their spin Hamiltonian a formula for the magnetic fields at which lines should occur. This approximate formula agrees satisfactorily with observations only when the angle $\theta$ between magnetic field direction and $z'$ axis is less than 70°. For LiF we can now obtain from a secular equation exact eigenvalues of the same spin Hamiltonian for all $\theta$. By giving the constants $a$, $b$ appropriate signs and magnitudes we can explain the observed position of every line for any angle $\theta$. This increases our confindence in the correctness of the original interpretation[1] of the spectra observed in irradiated alkali halides at −180°C.

[1] W. Kanzig, Phys. Rev. **99**, 1890 (1955); T. G. Castner and W. Känzig (to be published).

**Y8. Emission of *Z*-Centers in KCl.** E. J. WEST AND W. DALE COMPTON, *U. S. Naval Research Laboratory*.—Excitation and emission experiments have been made on KCl crystals containing 0.013 M% $SrCl_2$ and additively colored at 600°C with potassium. The crystals were slowly quenched. Absorption measurements at 77°K on freshly cleaved crystals showed peaks at 545, 630, and 810 mμ corresponding to the $F$, $Z_2$, and $M$ bands, respectively. Excitation spectra at 77°K showed well-defined peaks at these wavelengths. The emission at 77°K peaked at 1.07 μ for $F$- or $M$-band excitation and 1.17 μ for $Z_2$-band excitation. Irradiation with $F$ light at 300°K produced a band at 850 mμ and the $Z_1$ band at 590 mμ. The $F$, $M$, and $Z_2$ bands were partially bleached by this light. Excitation peaks were now found at 590, 630, and 850 mμ but not at the $F$- or $M$-band positions. Emission at 77°K with excitation in the $Z_1$-band region was found to have two peaks—a short wavelength peak lying between 1.1 and 1.2 μ and a long wavelength peak at 1.70 μ. Excitation at 850 mμ gave only the 1.70 μ emission. The efficiency of the excitation of the 1.70 μ emission was about the same at 300°K and 77°K.

**Y9. Color Centers in Lithium Hydride.*** FRANK E. PRETZEL, *Los Alamos Scientific Laboratory*.—Single crystals of lithium hydride have been prepared by slow crystallization of the melt under hydrogen gas. The problem of impurities, particularly $O^=$ and $Mg^{++}$, is considered. The best crystals have been prepared by synthesizing the salt from freshly distilled lithium metal and purified hydrogen in the crucible inside the apparatus, just before crystallization. Single crystals have been used to prepare samples to study the effects of irradiation on optical absorption properties. The $F$ band is found at 2.19 ±0.02 ev in LiH and 2.22±0.02 ev in LiD at 77°K. X-irradiation of lithium hydride at 77°K forms many bands which obscure the $F$ band. Most of these bands bleach out quickly at room temperature. The $F$ band is readily bleached by $F$ light at 77°K to form the $F'$ band, which is thermally unstable above 160°K. The colloidal lithium band is readily formed at room temperature in samples containing about $10^{16}$ $F$ centers/cc or more. Some mechanism also exists for the slow dissolution of lithium colloid in LiH to re-form $F$ centers at room temperature.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

**Y10. Structure of the Occupied Energy Bands of KCl.** L. P. HOWLAND, *M.I.T.*—The band structure of KCl was calculated in a many-electron, tight-binding approximation. In this the wave function for the whole crystal was taken to be a single determinant of Hartree-Fock functions for the free ions of potassium and chlorine centered on crystal lattice sites. Approximate Hartree-Fock functions for the crystal were determined as linear combinations of free-ion functions, and the band structure was obtained from the values of the corresponding approximate Hartree-Fock energy parameters. The band structure was obtained for various values of the interionic distance, and the cohesive energy of the crystal was calculated for one of the distances. The width of the valence band for the normal interionic distance was determined to be about 1.5 electron volts. The general method has been extended to a preliminary study of the simplest $V$ center in KCl.

**Y11. Oscillator Strengths for Luminescent Transitions in KCl:Tl and KCl:In.** F. E. WILLIAMS, B. SEGALL, AND P. D. JOHNSON, *General Electric Research Laboratory*.—Crystalline interactions are important in the calculation of transition energies for KCl:Tl.[1] In the present work we have studied theoretically the ratios of oscillator strengths for the two principal impurity absorption bands in KCl:Tl and KCl:In, including the effect of crystalline interactions. These interactions were neglected in another analysis of this problem.[2] We introduce spin-orbit interaction after including the larger crystalline interactions. The excited impurity states are assumed to be of the nature of $^1P_1{}^0$ and $^3P_1{}^0$ states of the $sp$ configuration. Since spin-orbit coupling constants are determined by wave functions well within the ion core, the values obtained from free ion spectra are a suitable approximation. Experimental transition energies for the crystal are utilized to calculate the energy separation of the pure singlet and triplet states. The calculated oscillator strength ratios are in satisfactory agreement with experiment. Crystalline interactions reduce the energy separation of the pure singlet and triplet states of the free ion. It is possible to account for part of the reduction in energy separation by the difference in radial wave functions of these states.

[1] F. E. Williams, J. Chem. Phys. **19**, 457 (1951).
[2] R. S. Knox and D. L. Dexter, Phys. Rev. **104**, 1245 (1956).

**Y12. Electro-Photoluminescent Amplification.** RICHARD E. HALSTED, *General Electric Research Laboratory*.—Preliminary results of an investigation for a correlation of dielectric constant and loss measurements[1] with the charge transport revealed by electrophotoluminescent modulation in nonuniformly excited sulfide phosphor samples[2] will be described. It was found that alternating electric fields can modify the time distribution of luminescent recombination in these materials with the expenditure of less electrical energy than is contained in the fluctuating component of the emitted visible radiation. Within the range of excitation intensity, frequency, and voltage where this is true the phosphor sample may be regarded as an amplifier, deriving its power from incident radiation, which converts an applied electrical signal into an output light signal with energy gain and frequency fidelity.

[1] S. Roberts, J. Opt. Soc. Am. **43**, 590 (1953).
[2] R. E. Halsted, Phys. Rev. **99**, 1897 (1955).

**Y13. Light Output of an Electroluminescence Cell Excited by Short Voltage Pulses.** GEORGE R. BRIGGS, *RCA Laboratories*.—Total light output has been measured and output

wave forms obtained for a green electroluminescent cell excited by short pulses of voltage. The phosphor was a ZnSe :ZnS solid solution type embedded in a 0.5-mil plastic layer. Rectangular pulses and pulses having one or both edges of exponential shape between 2 and 40 μsec in duration were applied. Reddish light is emitted during and after both the rise and fall of the pulse while bluish light is emitted predominantly after the pulse starts to fall. With a slowly falling pulse the light associated with the fall is delayed until the pulse is nearly zero. Slowly rising pulses excite relatively more blue light and slowly falling pulses more red light. The light obeys an $\exp(-bV^{-\frac{1}{2}})$ law for all colors and all pulse shapes investigated. Cell-current flow and loss data are also presented.

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## SATURDAY AFTERNOON AT 1:30

Physical Sciences, Room A-1

(W. L. BROWN presiding)

### *Irradiation Effects; Semiconductors*

**Z1. Orientation Dependence and Threshold Energy of Radiation Damage in Germanium.** W. L. BROWN AND W. M. AUGUSTYNIAK, *Bell Telephone Laboratories.*—An orientation dependence has been found in the rate of introduction of radiation damage in germanium by monoenergetic electrons near the energy threshold. The damage has been measured through the decrease it produces in the electrical conductivity of *n*-type material, the irradiations and the electrical measurements being made at liquid nitrogen temperature. With the incident electron oriented in the (111) direction with respect to the crystal, the damage rate is as much as 40% higher than in either the (110) or (100) directions. The difference decreases at higher energies. In connection with his calculations of the energy threshold W. Kohn[1] has suggested the possibility of an orientation dependence corresponding to the anisotropy of the potential profile for atomic displacement arising from the bond structure of an individual atom. The (111) direction is favored in the simplest picture, in agreement with the present measurements. The actual threshold energy determined in these experiments appears to be about 0.4 Mev compared with the lifetime threshold of 0.5 Mev reported by Loferski and Rappaport and the earlier conductivity threshold of 0.63 Mev determined by Klontz and Lark-Horovitz. There is, however, evidence that some damage occurs even below 0.4 Mev.

[1] W. Kohn, Phys. Rev. **94**, 1409 (1954), and private communication.

**Z2. Effects of Multiple Scattering of Electrons on the Production of Defects in Fast Electron Bombardment of Germanium.*** J. W. MACKAY AND E. E. KLONTZ, *Purdue University.*—It is generally assumed that electron bombardment of samples thin compared to the range of the incident electrons results in nearly uniform production of defects throughout the sample. Usually the only correction which is considered is the decrease in cross section due to the energy loss in penetrating the sample. The effect of multiple scattering increases the path of the electron and results in an increase in defect production. For the case of germanium, calculations indicate that the effect of multiple scattering outweighs the effect of energy loss, and the production of defects should increase with depth of penetration. For a sample of infinite area with uniform bombardment at 4 Mev, this increase amounts to about 15% at a depth of 400 μ. A second effect of the multiple scattering is that electrons are scattered out of the edges of the sample, producing a nonuniform defect distribution across the sample. Variations in defect concentration cause a nonuniform carrier concentration. Experimental results are presented showing the effect of nonuniform carrier concentration in bombarded Ge and the effect of sample thickness on the measured rate of carrier removal $dn/d\phi$.

* Work supported by U. S. Atomic Energy Commission contract.

**Z3. Theory of Diffusion Limited Reactions; Annealing of Radiation Damage in Germanium.** T. R. WAITE, *Bell Telephone Laboratories* (introduced by N. B. Hannay).—A theory has been developed describing the kinetics of the diffusion limited reaction $A+B\rightarrow AB$. The joint probability distribution of each $AB$ pair in the system is considered. The differential equations describing the alteration of these densities due to diffusion and reaction have been derived. The competition of all of the $A$'s for each of the $B$'s (and vice versa) and the removal of particles from the system upon reaction have been appropriately accounted for. Complete analytic solutions may be obtained for a variety of boundary conditions. An attempt has been made to treat the data of Brown, Fletcher, and Wright[1] and of Augustyniak[2] on the isothermal annealing of radiation damage produced in germanium by 3-Mev electrons. The damage is believed to have consisted of randomly distributed vacancy-interstitial pairs which annealed by the diffusion together of interstitials and vacancies. A reasonable fit of the data has been obtained with the present theory. Information concerning the diffusion constants ($E^* \cong 32$ kcal/mole) and the distribution of interstitials about the vacancies from which they were dislodged (average displacement $\sim 1.5$ times the capture radius) have been obtained from the annealing data.

[1] Brown, Fletcher, and Wright, Phys. Rev. **92**, 591 (1953).
[2] W. Augustyniak (personal communication).

**Z4. *n*-Type Deuteron Irradiated Germanium—Low Temperature Carrier Removal Rates.*** D. KLEITMAN AND K. LARK-HOROVITZ, *Purdue University.*—The rate of conduction electron removal as a function of irradiating deuteron flux is dependent upon the Fermi level for *n*-type germanium. Removal rate $(-dn/d\phi)$ or $(-\Delta n/\phi)$ *vs* $\xi$ level data can be used[1] to locate energy levels introduced in the forbidden band by bombardment. Measurements were made of the Hall effect and resistivity of numerous 100 μ thick *n*-type germanium specimens as they underwent varying amounts of irradiation with 9.6-Mev deuterons. At 85°K a large increase (3 to 1) in removal rates for samples with $\xi > (E_{cb} - 0.025 \pm 0.01$ ev) indicates major bombardment introduced levels at this energy, whereas a flat region for $(E_{cb} - 0.035$ ev$) > \xi > (E_{cb} - 0.1$ ev) suggests only few, if any, levels introduced here. At 205°K four samples irradiated with $(E_{cb} - 0.1$ ev$) > \xi > (E_{cb} - 0.22$ ev) suggest again the absence of major levels in that region. The highest removal rates observed with impure samples at 85°K $(-dn/d\phi \sim 1100)$ may be compared with the recently revised theoretical estimate (assuming a 30-ev displacement threshold) of 1280 for $(dN/d\phi)$, $N$ the vacancy interstitial pair density.

Mobility changes with bombardment were studied as were effects of annealing at temperatures up to 300°K.

* Work supported by a U. S. Signal Corps contract.

[1] H. Y. Fan and K. Lark-Horovitz, "Defects in crystalline solids," Report of the 1954 Bristol Conference.

**Z5. Irradiation of Silicon with 9.6 Mev Deuterons.*** T. A. Longo and K. Lark-Horovitz, *Purdue University.*—Both *n*- and *p*-type silicon were irradiated with 9.6-Mev deuterons. The Hall coefficient and conductivity of degenerate and nondegenerate samples were measured as a function of irradiation. The carrier concentrations of all samples were reduced by irradiation. For *n*-type degenerate samples the carrier removal rate $\Delta n/\phi = -670$ electrons deut.$^{-1}$ cm$^{-1}$ and for *p*-type degenerate $\Delta p/\phi = -750$ holes deut.$^{-1}$ cm$^{-1}$. These compare favorably with a calculated rate of defect pair introduction of $\Delta N_D/\phi = 775$ defect pairs deut.$^{-1}$ cm$^{-1}$, with one carrier removed per pair. This work supports the belief that the introduction of vacancy interstitial pairs are the predominant effect of irradiation. The removal rates decrease rapidly as the Fermi level moves into the forbidden gap. The interstitial states appears to be at 0.025 ev from conduction band and the vacancy states at 0.055 ev from the valence band. For heavy irradiations the removal rates are lower in the degenerate and higher in the nondegenerate regions than with smaller irradiations. This suggests clustering of defects, with states associated with these clusters being introduced deep in the forbidden gap.

* This work supported in part by the U. S. Signal Corps.

**Z6. X-Ray Diffuse Scattering Measurements of Pile-Irradiated Germanium Single Crystals.*** Roger Chang, *Atomics International.*—The x-ray diffuse intensity near the (333) reciprocal lattice, along a direction passing through the reciprocal lattice point and the origin, of pile-irradiated germanium single crystals was measured. The germanium single crystals, cut parallel to (111) plane, were irradiated in the ORNL graphite reactor at about 20°C to integrated fast neutron fluxes of $10^{18}$ to $10^{18}$ *n*/cm$^2$. The results can be summarized as follows: (1) calculations from the diffuse intensity of unirradiated specimens yield reasonable values of the velocity of longitudinal waves along the direction of measurement; (2) the radiation induced diffuse intensity increases with increasing time of exposure, though not linearly; (3) the radiation induced diffuse intensity can be removed by annealing. At present the data cannot be interpreted satisfactorily in terms of the production of randomly distributed point defects such as vacancies and interstititals. A new interpretation, based on the accumulation of centers of distortion due to thermal spikes or displacement spikes, will be discussed briefly.

* This work was supported by the Research Division of the U. S. Atomic Energy Commission.

**Z7. Structure Spikes in Deuteron-Irradiated III–V Compounds.** U. Gonser (introduced by J. S. Koehler).*—The III–V compounds represent one of the few systems where large effects are observed to result from the presence of the thermal spikes which occur during heavy particle irradiation. Single crystals of GaSb and InSb were irradiated at liquid nitrogen temperature with approximately $2\times10^{17}$ 12-Mev deuterons/cm$^2$. The change in intensity and shape of the x-ray reflections showed that spike regions exist and that the material contracts on irradiation. It is reasonable to assume that the following reaction takes place:

$$\mathrm{GaSb}_{\text{solid configuration}} \underset{\text{annealing}}{\overset{\text{radiation}}{\rightleftharpoons}} \mathrm{GaSb}_{\text{liquid configuration}}.$$

The spikes have the liquid structure with a higher density and 8 nearest neighbors instead of 4 in the solid (zinc blende). If the liquid structure of these III–V compounds exists with long-range order, a modified Debye-Scherrer method can be applied. Broad Debye-Scherrer rings (4 lines) were observed in the irradiated specimens which indicate that the structure of the spikes corresponds to a body-centered tetragonal lattice. The model of a "displacement spike" can be altered for these materials.

* Work supported in part by the U. S. Atomic Energy Commission.

**Z8. Effect of Irradiation on the Hole Lifetime of *n*-Type Ge.*** O. L. Curtis, Jr., J. W. Cleland, and J. C. Pigg, *Oak Ridge National Laboratory.*—The effect of irradiation at room temperature on the minority carrier lifetime of high-purity single crystal *n*-type Ge has been studied using a transient measurement of the decay of holes following injection by a surface-barrier contact. The irradiations were conducted in the ORNL graphite reactor and a $Co^{60}$ gamma-ray source. The minority carrier lifetime is extremely sensitive to such irradiations. The lifetime is decreased by fast neutrons at a rate that is initially several orders of magnitude greater than the observed carrier concentration decrease. The lifetime is also decreased by gamma irradiations; however, the decrease in lifetime appears to be less for a given change in carrier concentration than was observed with fast neutrons. A logarithmic plot of $(1/\tau - 1/\tau_0)$ (a measure of the change in recombination probability) *vs* $\phi$, the total flux integrated over time, indicates a simple power dependence; however, the observed straight line has a slope which is less than unity.

* This work was supported by the U. S. Atomic Energy Commission.

**Z9. Radiative Recombination in Semiconductors as an Indicator of Radiation Damage.** R. Braunstein, *RCA Laboratories.*—The radiative recombination of electron-hole pairs has been observed from Ge and Si[1] and a number of III–V semiconductors.[2] An estimate of the radiative recombination rate can be made by using the known optical constants of a semiconductor and applying the principle of detailed balance. Direct electron-hole recombination is an intrinsic property of the material, whereas recombination via traps is structure sensitive. The number of photons emitted, for a given generation of electron-hole pairs, is proportional to the ratio of the lifetime resulting from traps to the radiative lifetime. It is difficult to obtain quantitative data on the intensity of the emitted recombination radiation, because of internal reflections in the samples and the poor collection efficiency. However, it is possible to measure the decay of the recombination by introducing structural defects in the crystal. The results of a study of the decay of the radiation signal from *n*- and *p*-type Ge under $\beta$-ray bombardment will be presented. The rate of decay is slower for *p* type than *n* type and is resistivity-dependent. This method should be useful in measuring radiation damage on materials where other methods of determining lifetime are not convenient.

[1] J. R. Haynes and H. B. Briggs, Phys. Rev. **86**, 647(A) (1952).
[2] R. Braunstein, Phys. Rev. **99**, 1892 (1955).

**Z10. Cryostat for Reactor Irradiation of Samples.** C. C. Sartain and H. P. Yockey, *Oak Ridge National Laboratory.*—A cryostat for continuously bathing samples in liquid nitrogen or other heat transfer liquids during nuclear reactor irradiation has been constructed and successfully operated. The samples to be irradiated at low temperature are immersed in the heat transfer fluid which is high-purity liquified nitrogen circulating in a closed system at a pressure greater than that of the atmosphere. The liquid is kept below its boiling point throughout its cycle by use of a heat exchanger located outside the reactor shield. The heat exchanger is cooled by commercial liquid nitrogen boiling at atmospheric pressure. Since oxygen and water vapor from the air cannot enter the closed

pressurized system, no chemical explosions inside the nuclear reactor due to an ozone reaction or from recombination of disassociated water have occurred. There has been to date no evidence of any formation of an aluminum-nitrogen compound such as has been postulated to cause chemical explosions in aluminum dewars filled with liquid nitrogen and inserted into nuclear reactors. Baths at other temperatures may be obtained by substituting suitable liquids for the high-purity nitrogen heat transfer fluid and by keeping the heat exchanger at the desired temperature.

## SUPPLEMENTARY PROGRAMME

**SP1. Electron Drift Mobility and Hall Mobility of 1900 ohm-cm (Uncompensated) *p*-Type Silicon.*** MILTON GREEN, *Signal Corps Engineering Laboratories.*—Since experimentally measured values of Hall mobility and electron drift mobility for *p*-type silicon have not been reported as yet, for resistivities in excess of 200 ohm-cm, it was thought that it would be of interest to make such a report on the results obtained on a silicon sample having 1900 ohm-cm resistivity. The sample was produced in vacuum by the floating zone technique. It was found that Hall mobility ($R\sigma$) was 450 cm²/volt sec at room temperature, estimated as being correct to within 5%. This is in good agreement with the asymptotic value approached by the curve of Debye and Kohane.[1] The electronic drift mobility, measured by the constriction method, was found to be 1510 cm²/volt sec at room temperature. This value is in agreement with values obtained by extrapolation of the curves of Prince[2] and Ludwig and Watters.[3] The effective lifetime of the sample for the minority carriers was 700 microseconds.

* To be called for at the end of Session X if the Chairman rules that time suffices.

[1] P. P. Debye and T. Kohane, Phys. Rev. **94**, 724 (1954).
[2] M. P. Prince, Phys. Rev. **93**, 1204 (1954).
[3] G. W. Ludwig and R. L. Waters, Phys. Rev. **101**, 1699 (1956).

# Author Index to Papers Presented at the 1957 Philadelphia Meeting


Alers, G. A.—B7, CA1
Allan, A. J. G.—D5
Allgaier, Robert S.—Q10
Amar, Henri—B1
Andrews, R. D.—V2
Antal, J. J.—VA6
Arai, T.—HA9
Arrott, A.—B3, B9, B12
Asendorf, R. H.—T8
Atkins, K. R.—LA11, P1
Augustyniak, W. M.—Z1

Babiskin, J.—Q3
Backenstonss, G.—K4
Bacon, R.—H11
Balkanski, M.—C7
Balluffi, R. W.—LA7, VA10
Barkow, A. G.—R3
Bate, R. T.—Y4
Batterman, B. W.—RA8
Bauerle, J. E.—RA12, RA13
Becker, J. H.—C6
Beer, A. C.—Q11
Bendel, W. L.—R6
Benedek, G. B.—J2
Berlincourt, Ted G.—LA3
Bernstein, B.—H3
Bettelheim, F. A.—V4, V5
Bhatia, A. B.—T3
Billmeyer, Fred W., Jr.—N3
Blakemore, J. S.—X5
Blatt, F. J.—Q5
Blewitt, T. H.—VA7, VA8, VA9
Blue, M. D.—K14
Bogart, L.—R1
Bowman, J. C.—H11, LA9
Brandt, W. Wilfried—D9
Braunstein, R.—Z9
Bray, R.—X7
Briggs, George R.—Y13
Brown, F. C.—C4
Brown, W. L.—Z1
Bruce, C. R.—G15
Brueckner, K. A.—W1
Buckser, S.—V4
Burnett, B. B.—M2
Burstein, E.—F5, Q5
Busse, W. F.—D10

Cable, J. W.—G3, G4
Cabrera, N.—H10
Caldwell, R. S.—K13
Callen, Herbert B.—G7, G8, HA7
Canty, B. F.—HA5
Carr, W. J., Jr.—R8
Caspari, M. E.—Y1, Y2
Chamany, B.—R3
Chambers, R. H.—RA3, RA4
Champion, K. S. W.—HA4
Chang, Roger—Z6
Child, William C., Jr.—E4, E5
Chupka, W. A.—U2
Chynoweth, A. G.—X8
Cleland, J. W.—K2, Z8
Cohen, Alvin J.—VA5
Cohen, D. A.—C8
Cole, G. R.—Y6
Cole, R. H.—A3
Coleman, R. V.—H10
Collins, R. L.—N9
Coltman, R. R.—VA7, VA8
Compton, W. Dale—Y8
Cooper, H. W.—B3
Cotts, R. M.—S2
Crawford, J. H., Jr.—K2
Curtis, O. L., Jr.—Z8

Danielson, G. C.—C5, K14
Dannhauser, Walter—E5
Dash, J. G.—LA10
Dash, W. C.—RA9
Decker, D. L.—LA6
Deeley, C. W.—E7
Dienes, G. J.—VA6
Dillon, J. F., Jr.—G12
Di Marzio, E. A.—D3
Dousmanis, George C.—H4
Doyama, Masao—Y5
Dubey, V. S.—R4

Enrietto, J.—CA5
Eskowitz, A.—G13

Fairbank, W. M.—P3
Faire, A. C.—HA4
Fan, H. Y.—C9, K13
Fang, P. H.—HA3
Feder, R.—CA4
Feher, G.—S1
Ferrell, Richard A.—T2
Ferry, John D.—E4, E5, E6
Fiegel, L. J.—X9
Fischbach, D. B.—CA6
Fitzgerald, Edwin R.—E8
Flory, F. J.—M3
Foner, Simon—G11
Franklin, A. D.—HA5
Freistadt, Hans—R9
Friauf, R. J.—Y6
Fritzsche, H.—H1, K5
Fuschillo, N.—E3

Galt, J. K.—F3
Gibbs, J. H.—D3
Gibbs, Peter—RA5
Gibson, John B.—T7
Gilles, P. A.—U1
Gilman, J. J.—RA6, RA7
Glicksman, Maurice—Q12
Gobeli, G. W.—C9
Godard, Grace N.—N6
Goldberg, C.—X1
Goldman, J. E.—B6, B12
Gonser, U.—Z7
Grace, M. A.—LA2
Grant, F. A.—HA2
Green, Milton—X10, SP1
Gruntfest, I. J.—D7
Gurnee, E. F.—V3

Hagstrum, Homer D.—K1
Hake, R. R.—LA6
Halsted, Richard E.—Y12
Harrison, S. E.—G10
Hart, Edward W.—RA10
Heer, C. V.—Y4
Heller, Wilfried—V6, V7, V8
Henvis, B.—K12
Herman, F.—T1
Hoffman, J. D.—A4
Holcomb, D. F.—G14
Howland, L. P.—Y10
Hughes, R. E.—M1

Isaacson, Leonard—HA10

Jacobs, I. S.—B2
Jamison, R. E.—VA11
Johnson, C. E.—LA2
Johnson, E. O.—H5
Johnson, P. D.—Y11
Johnston, W. G.—RA6, RA7
Jona, F.—G2

Känzig, Werner—Y7
Kaplan, Harvey—T10
Karplus, Martin—HA10
Kauffman, J. W.—RA11
Keefer, D.—CA8
Keffer, F.—B10, C1, C2
Kellett, Claud M.—H1
Keyes, R. J.—F4
Klabunde, C. E.—VA7, VA8
Klein, Abraham—L4
Kleitman, D.—Z4
Klevens, H. B.—VA4
Klontz, E. E.—Z2
Kobayashi, Koichi—VA1, VA2
Koehler, J. S.—RA12, RA13
Koehler, W. C.—G3, G4
Koistinen, D. P.—CA7
Konitzer, John D.—Y3
Kooch, Walter—D7
Kriessman, C. J.—G10
Krimm, S.—N8
Kunzler, J. E.—LA4
Kuppermann, Aron—HA10
Kurti, N.—LA2

Lampert, Murray A.—X3
Lark-Horovitz, K.—H1, K5, Z4, Z5
Lax, Benjamin—Q6, Q7, Q8
Lax, M.—T4
Lehman, Guy W.—T9
Levy, Paul W.—VA3
Liang, C. Y.—N8
Litovitz, T. A.—D1
Longo, T. A.—Z5
Lowe, I.—J5
Luttinger, J. M.—W3

MacKay, J. W.—Z2
Madigan, J. R.—X9
Mandelkern, L.—N4
Mandeville, C. E.—R4
Mapother, D. E.—LA6
Marburger, R. E.—CA7, CA11
Margrave, J. L.—U3
Markham, Jordan J.—T5, Y3
Matossi, Frank—X4
Matthias, B. J.—A1
McCall, D. W.—D4, E2
McCarthy, C. S., Jr.—H3
McClure, J. W.—Q2

**McDevit, W. F.**—M2
**McKay, K. G.**—X8
**McKelvey, J. P.**—X6
**Meers, J. T.**—LA9
**Mendelson, K.**—X7
**Meshii, M.**—RA11
**Metzger, F. R.**—L2
**Miller, P. H., Jr.**—HA1
**Miller, R. L.**—E1
**Mooney, M.**—CA4
**Morin, F. J.**—K10
**Morris, R. G.**—C5
**Morrison, S. Roy**—H2
**Mozer, B.**—VA1
**Muldawer, L.**—RA1

**Nakagaki, Masayuki**—V7, V8
**Nathan, Marshall I.**—K7
**Neighbours, J. R.**—B7, CA1
**Neimark, J. E.**—D10
**Neuringer, L. J.**—K3
**Newman, Sanford B.**—D6
**Noggle, T. S.**—VA7, VA8
**Nowick, A. S.**—CA4, CA9, CA10

**Orowan, E.**—D10
**O'Sullivan, W.**—B10

**Pao, Y. H.**—V1
**Parikh, N. M.**—B6
**Paul, William**—K7
**Paxton, H. W.**—B3
**Pearlstein, E.**—VA1
**Pell, E. M.**—K9
**Pepinsky, R.**—G2
**Peterlin, Anton**—V7
**Petritz, Richard L.**—H9
**Pfann, W. G.**—RA8
**Philippoff, Wladimir**—V9
**Pigg, J. C.**—Z8
**Piper, William W.**—HA6
**Pittelli, Ernest E.**—G8
**Plazek, D. J.**—E6
**Pollack, S. R.**—G10
**Porter, W. C.**—R5
**Potter, Roy F.**—C10
**Powell, Robert L.**—LA8
**Pratt, G. W., Jr.**—B8
**Pretzel, Frank E.**—Y9

**Rado, George T.**—G6
**Redfield, A. G.**—J1
**Redfield, David**—C11
**Redin, R. D.**—C5
**Redman, J. K.**—VA9
**Reich, H. A.**—P4
**Reid, F. J.**—Y4
**Reif, F.**—J4
**Reiss, H.**—K10
**Reitz, J. R.**—C8
**Renton, C. A.**—LA4
**Riste, T.**—G5
**Roberts, D. E.**—N4
**Roberts, T. R.**—P2
**Rodbell, D. S.**—G9
**Roder, Hans M.**—LA8
**Ross, J.**—W2
**Roswell, A. E.**—CA9
**Roth, Laura M.**—Q7, Q8
**Roth, W. L.**—B11
**Rothman, M. A.**—R5
**Rothstein, Jerome**—CA3
**Rudd, J. F.**—V2, V3

**Salkovitz, E. I.**—B5
**Sartain, C. C.**—Z10
**Sato, Hirsohi**—B7, B9, LA5
**Sauer, J. A.**—E3, E7
**Scanlon, Wayne W.**—Q10
**Schindler, A. I.**—B5
**Schluchter, A. W.**—CA11
**Schoen, A. H.**—CA12
**Schultz, Harvey**—HA1
**Schultz, M. L.**—K11
**Sclar, N.**—K12
**Scott, K. W.**—N2
**Scott, R. G.**—N5
**Scovil, D.**—S4
**Scurlock, R. G.**—LA2
**Searcy, A. W.**—U4
**Segall, B.**—Y11
**Seitz, Frederick**—R2
**Selove, Walter**—L3
**Seraphim, D. P.**—CA10
**Shirane, G.**—G2
**Shulman, R. G.**—J3
**Siebenmann, P. G.**—Q3
**Simmons, R. O.**—LA7, VA10
**Sladek, R. J.**—Q9
**Slichter, W. P.**—E2
**Smilowitz, B.**—C2
**Smith, Charles S.**—CA2
**Smith, Herbert L.**—VA5
**Smith, R. J.**—B5
**Smith, R. W.**—C12
**Smoluchowski, R.**—RA2, RA3, RA4
**Smyth, C. P.**—A2
**Sochard, I. I.**—C6
**Sonder, E.**—K2
**Sorrows, Howard E.**—H8
**Soule, D. E.**—Q1
**Spangler, R. D.**—D8, D9
**Statton, W. O.**—N6
**Steele, M. C.**—F1
**Stein, Richard S.**—N7 ,V4, V5
**Stevens, D. K.**—K2
**Sturm, W. J.**—K2
**Suzuki, Taira**—Y5
**Swann, W. F. G.**—L1
**Swanson, J. A.**—F2
**Swartz, George A.**—K6

**Tanttila, W. H.**—S3
**Tauber, G. E.**—T3
**Taylor, R. Dean**—LA10
**Taylor, R. T.**—LA2
**Tenzer, L.**—G5
**Tinkham, M.**—LA1
**Tobolsky, A. V.**—N1
**Tomizuka, C. T.**—CA13
**Triebwasser, Sol**—G1
**Tyler, W. W.**—K8

**Ufford, C. W.**—HA7
**Unterleitner, F.**—G2

**Van Patter, D. M.**—R5
**van Roosbroeck, W.**—X2
**Van Sciver, W. J.**—R1
**Vassamillet, L.**—RA2

**Waite, T. R.**—Z3
**Wallis, G.**—H6, H7
**Wallis, Richard F.**—Q4, Q5
**Wang, S.**—H6, H7
**Wangsness, R. K.**—G13
**Watson, K. M.**—W4
**Wert, C.**—CA5, CA8
**West, E. J.**—Y8
**Wheatley, G. H.**—C3
**Whelan, J. M.**—C3
**Widom, B.**—HA8
**Wilkinson, M. K.**—G3, G4
**Willardson, R. K.**—Q11
**Williams, F. E.**—Y11
**Winder, D. R.**—CA2
**Witmer, Enos E.**—R7
**Wolf, W. P.**—B4
**Wollan, E. O.**—G3, G4
**Wolock, Irvin**—D6
**Wood, Lawrence A.**—D2
**Woodbury, H. H.**—K8
**Woodruff, Truman O.**—Y7
**Woodward, A. E.**—E7

**Yamashita, Jiro**—T6
**Yockey, H. P.**—Z10
**Yoshikawa, H.**—Y1, Y2
**Young, E. M., Jr.**—D7

**Zemel, Jay N.**—H9
**Zwerdling, S.**—Q6, Q7, Q8

## Second Announcement of the 1957 Spring Meeting

The 1957 Spring Meeting of the American Physical Society will be held in Washington, D. C., at the Sheraton-Park and Shoreham Hotels and the National Bureau of Standards, on Thursday, Friday, and Saturday, April 25, 26, and 27. Room reservations are to be made by writing to the Sheraton-Park Hotel, Washington 8, D. C., and specifying that the writer is a member of the Society. The Sheraton-Park undertakes to provide rooms in other hotels after its own allotment to our members is fully booked: our members may designate the hotels of their choice. Deadline will be Friday, February 15, 1957. Abstracts for this meeting must be received not later than this date at the office of the American Physical Society, Columbia University, New York 27, New York.

## MEETINGS AND DEADLINES FOR THE SEASON 1956–1957

| *Place* | *Meeting dates* | *Deadline date* |
|---|---|---|
| Norman, Oklahoma | March 1–2 | Past |
| Philadelphia | March 21–23 | Past |
| Washington, D. C. | April 25–27 | Past |
| Notre Dame, Indiana | June 20–22 | April 12 |
| Boulder,* Colorado | September 5–7 | July 8 |

* Abstracts for the Boulder meeting are to be sent to W. A. NIERENBERG, University of California, Berkeley 4, California, and must reach his office not later than the corresponding deadline date.

Abstracts for the other meetings listed above are to be sent to KARL K. DARROW, American Physical Society, Columbia University, New York 27, New York, and must reach his office not later than the corresponding deadline date. Take note that abstracts mailed the day before deadline day often fail to arrive in time: the last postal delivery of the day usually comes to our office before 2 P.M. Allow at least two days for abstracts sent by air-mail from points east of the Mississippi, and longer for those sent from farther west. To avoid chance of confusion, please do not send an abstract for any meeting until the deadline date of the previous meeting is at least five days past. *The privilege of contributing papers to meetings of the American Physical Society is restricted to the members of the Society and to nonmembers whose papers are sponsored by members.*

## RULES PRESCRIBED FOR ABSTRACTS

The Council has ordered that abstracts shall be not longer than two hundred (200) words or the equivalent thereof. In reckoning equivalence, a footnote is equated to ten words; each line in a table to ten words; a "display" formula—one that requires a line to itself—is an expensive luxury equated to forty words.

Two copies of each abstract must be sent to the appropriate office. They must be typewritten and **double-spaced**; one must be an original, the other may be an original or a carbon copy. Each abstract must be confined to a single page: if it is too long for a single page it is too long to be printed. *Henceforth, if we receive an abstract typed on two pages, we shall print only its first page.* Write each abstract as a single paragraph: the suppression of paragraphs costs time and labor to the editors. Do not use very thin paper; a sheet of very thin paper may cause extraordinary trouble when mixed with sheets of reasonable thickness. Look at the abstracts in this *Bulletin* to see how the title of the paper and the name of the author are to be arranged, and follow the example. Issues of the *Bulletin* are sometimes appreciably delayed because the editors have to do what the authors should have done.

Remember the rule of the Council that, if an author submits more than one abstract, all but one must go onto the Supplementary Programme. In enforcing this rule, an abstract is credited to the author whose name appears first in the by-line. **By action of our Council, abstracts will not henceforth be withdrawn from our proofs unless the asker sends ten dollars with his request.**

# Proceedings of the American Physical Society*

MINUTES OF THE WINTER MEETING ON THE WEST COAST
HELD AT THE U. S. NAVAL POSTGRADUATE SCHOOL,
MONTEREY, CALIFORNIA, DECEMBER 27, 28, 29, 1956

THE 1956 Winter Meeting on the West Coast of the American Physical Society was held at Monterey, California, on Thursday, Friday, and Saturday, December 27, 28, and 29. This was the first time that the meeting was held at the new quarters of the U. S. Naval Postgraduate School, which is situated on the beautiful grounds of the Del Monte Hotel. The weather was against us. It was sublimely beautiful, and it was very difficult to focus attention on the business part of the meeting. The facilities were excellent, and there is no question but that Monterey will become one of the regular places for the meeting of the American Physical Society if the appropriate invitations are issued.

There were 29 invited papers and 122 contributed papers. Of the latter, only one was read by title. This low percentage of unread papers also testified to the popularity of Monterey. We owe special thanks to Professor R. F. Bacher for arranging an excellent session on Astrophysics on Saturday morning.

The statistics are as follows:

The APS registration figure was 618.

The NCAPT had 25 additional nonduplicating registrations.

Banquet attendance was 417.

The members of the Society were guests at a cocktail party held before the dinner, and we are grateful to the hosts for the occasion, Firestone Research Corporation of Monterey. Another innovation was the serving of two kinds of wines at dinner. A special committee of "tastevins," Professors N. Kurti and W. B. Fretter, was formed for the occasion. Professor P. Kusch was the principal speaker on the subject of the social responsibilities of a Nobel Laureate. Professor R. T. Birge presided in place of President E. P. Wigner.

Our local chairman for the meeting was Professor E. C. Crittenden, Jr., and he is entitled to full credit for the details of a smoothly run meeting. The Monterey Chamber of Commerce was a great help, even to the extent of radioing the pilots of incoming planes to inform the arriving physicists that transportation awaited them.

W. A. NIERENBERG
*Local Secretary for the Pacific Coast*
University of California
Berkeley 4, California

* Minutes of the 1956 Chicago meeting will appear in a later issue of the Bulletin.

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## Errata Pertaining to Abstracts B11, S4, and S9 of the 1956 Monterey Bulletin (Series II, Volume 1, No. 8)

**B11,** by M. Annis, N. F. Harmon, and R. D. Sard. In line 16, instead of "2–5 Mev" read "2–5 Bev."

**S4,** by R. Bersohn and T. P. Das. In lines 2 and 3, instead of "$Mn^{++}$ is a typical $^1S_0$ ion" read "$Mn^{++}$ is a typical $S$-state ion ($^6S_{5/2}$)."

**S9,** by V. L. Pollak and R. E. Norberg. In line 16, instead of "2.0 microseconds" read "4.0 microseconds."

## Officers of Divisions That Are Convening at This Meeting

### Division of High-Polymer Physics

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To join any of these Divisions, apply to Secretary-Treasurer or to Treasurer thereof, sending check for $2 made out to respective Division. This privilege is reserved to members of the American Physical Society.

# The American Physical Society

## OFFICERS OF THE SOCIETY FOR 1957

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## COUNCIL

The President, Vice-President, Secretary, Treasurer, Managing Editor, the three Past Presidents most recently retired from office, eight elected members, and all Past Presidents first elected to the office of President prior to December 1932 constitute the Council which shall have general charge of the affairs of the Society.

*Past Presidents now on Council:* W. F. G. Swann, H. A. Bethe and R. T. Birge.

*Elected Members of the Council:* L. I. Schiff, W. Shockley, John Bardeen, A. O. Nier, F. Seitz, A. M. Weinberg, S. K. Allison, and N. F. Ramsey.

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*Please cut along this line*

**(To be sent to Mr. Solon D. Morgan, Department of Physics, University of Pennsylvania, Philadelphia 4, Pennsylvania.)**

I WISH to reserve . . . places for the banquet of the American Physical Society on Friday evening, March 22. (*If you wish to pay in advance send a check, made out to American Physical Society, for $5 per place.*)

I wish to reserve . . . places for the social hour on Thursday evening, March 21. (*If you wish to pay in advance, send a check, made out to American Physical Society, for $1.25 per place: omit such payment for a woman guest.*)

I wish to reserve . . . places for the tour of Philadelphia on Friday afternoon, March 22. (*If you wish to pay in advance, send a check, made out to American Physical Society, for $2.57 per place.*)

(*Name*) .....